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TECHNICAL REPORT

colour inside

Environmental conditions – Vibration and shock of electrotechnical equipment – Part 7: Transportation by rotary wing aircraft

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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 7: Transportation by rotary wing aircraft

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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IEC TR 62131-7, 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
104/839/DTR	104/854/RVDTR

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

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 "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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- withdrawn,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

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 7: Transportation by rotary wing aircraft

1 Scope

This part of IEC 62131, reviews the available dynamic data relating to the transportation of electrotechnical equipment by rotorcraft (helicopters). The intent is that from all the available data an environmental description will be generated and compared to that set out in IEC 60721 (all parts) [16][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 [21].

This document primarily addresses data extracted from a number of different sources for which reasonable confidence exist in its 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.

This document 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

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

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1 Numbers in square brackets refer to the bibliography.

4 Data source and quality

4.1 Vibration of Boeing CH-47 rotorcraft

A number of measurement exercises have been undertaken on the Boeing CH-47[2] rotorcraft, of those the measurements presented in [1] and [2] are typical. Many measurement exercises have focused on the vibration responses of carried goods, passengers and crew. However, the measurements of [1] and [2] were made specifically to characterize the vibration responses of the payload deck area within the rotorcraft.

The Boeing CH-47 rotorcraft is a twin rotor, twin engine heavy lift aircraft which first entered service in 1961. Although it is designed as a military aircraft, a number of commercial variants exists and those versions are widely used for the transportation of large or heavy equipment. They are also typically used to transport items to locations difficult to access by other means. The CH-47 is known by a number of different names including Chinook, Model 234 and Model 414. Also different designations arise indicating variants of the original design. The particular rotorcraft used in the measurement exercise was typical of most Boeing CH-47 variants with twin rotors each comprising three blades. The rotor shaft speed is around 225 rpm (3,75 Hz) giving a rotor blade passing frequency of 11,25 Hz.

The Boeing CH-47 was one of the fastest rotorcraft available when it first entered service and even today it is still amongst the fastest rotorcraft in commercial use. As rotorcraft vibration severities are strongly related to aircraft speed, an aspect which will be discussed later, the Boeing CH-47 is often used to set rotorcraft vibration severities for the transportation of equipment.

The cargo bay area of the Boeing CH-47 extends from frame 120 which is located just aft of the plane of the forward rotor to frame 482 which is located just forward of the plane of the aft rotor and attachment location of the twin engine. Frame 320 is located approximately in the centre of the length of the cargo bay area.

Rotorcraft generate a dominant vibration severity which commonly coincides with sensitivity of the human body to vibration. Indeed prolonged exposure to some rotorcraft vibrations can exceed recommended daily dosage to such vibrations. As a consequence, many rotorcraft vibration measurement exercises are aimed at quantifying human body exposure. However, the sensitivity of the human body to vibrations is predominantly biased towards the low frequencies, which are well below the frequency range normally considered for the testing of electrotechnical equipment. As such, measurement exercises made to quantifying human body exposure are mostly unsuitable for the purpose of this document. Moreover, a rotorcraft of concern from the viewpoint of human body exposure may not necessarily be of concern from the viewpoint of electrotechnical equipment. This is because the sensitivity of the human body is biased towards certain low frequencies.

The measurements of [1] and [2] on the Boeing CH-47 rotorcraft comprised twelve piezo-electric accelerometers and associated charge amplifiers. The vibration measurements were recorded on a 14-channel FM recorder. The system provided an effective measurement frequency range of 2,5 Hz to 2 500 Hz. The accelerometers were arranged in four mostly tri-axial groups placed on the cargo bay floor, along its length on the starboard side. Separate flights vibration measurements were additionally made on two payloads, each of approximately two tonne, carried within the cargo bay area. All the transducers were internally mounted on relatively stiff airframe locations.

Measurements were made during several flights and during a range of different flight conditions. Typically, vibration measurements on rotorcraft are made during a range of different steady state conditions. Such steady state conditions include hover and a variety of straight and level flight speeds at different altitudes. Additionally, vibration measurements are commonly made during a

2 Boeing CH-47 is the trade name of a product supplied by Boeing. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named.

variety of transient flight conditions. Such transient conditions include take-off, landing, transition to hover as well as transition to autorotation. Some of these transient conditions occur at some time on most flights whereas other conditions (such as transition to autorotation) may only be used in emergency or training situations. Transient conditions can be difficult to measure but can give rise to quite severe vibration severities. Steady state and transient vibration conditions can arise due to a number of mechanisms which are addressed in Clause 7.

The measurements of [1] and [2] on the Boeing CH-47 rotorcraft were analysed mostly in the form of acceleration power spectral densities (PSDs), although very few of these are presented in the reports referenced. Neither of the two reports indicates the record duration used for the power spectral density analysis. However, the analysis durations, typically used by the agency that made these measurements, is around 30 s for steady state conditions. With that said, durations will be more limited for the transient flight conditions and usually limited to the duration of the events, some of which only occur for a few seconds.

The approach used to quantify the vibration amplitudes at the rotor shaft, blade passing frequency and their harmonics, is a particular data analysis issue encountered when addressing rotorcraft vibration data. In this case the frequency analysis bandwidth is around 2,5 Hz. Whilst this is adequate to describe the broadband background vibration induced by rotorcraft, it is generally regarded as inadequate to quantify, in terms of power spectral density amplitude, the tones arising from the rotor blade passing frequency and the associated harmonics. For this reason the tones arising from the rotor blade passing frequency and subsequent associated harmonics, are quantified in terms of root mean square (RMS) values. The usual approach used by this measurement agency, was to compute the tonal component root mean square by integration of the power spectral density amplitudes for each tonal component. Reports [1] and [2] indicate that peak hold spectra were used (rather than the "average" power spectral density values) to estimate the amplitudes at rotor and blade passing frequencies.

Reports [1] and [2] present power spectral densities for selected flight conditions only. A number of these are reproduced in Figure 1 to Figure 4. These include straight and level flight at the rotorcraft's typical best sustained flight speed, during hover as well as during transient events of transition to hover and transition to autorotation. The reports mostly present severities in terms of root mean square values at rotor speed (3,75 Hz), the first harmonic of rotor speed (7,5 Hz), rotor blade passing frequency (11,25 Hz) and the next seven harmonics of rotor blade passing frequency (22,5 Hz, 33,75 Hz, 45 Hz, 56,25 Hz, 67,25 Hz, 78,5 Hz, 90 Hz). The reports also present the overall of root mean square values (2,5 Hz to 2 000 Hz). Some of this information is presented in this document as Figure 5 to Figure 14.

Compared in Figure 5 to Figure 10 are root mean square values for different flight conditions and for three locations along the floor of the cargo bay floor. The figures separately illustrate and compare the values of the overall of root mean square (2,5 Hz to 2 000 Hz), at rotor speed, blade passing as well as the second, third and fourth harmonic of blade passing. It should be noted that the overall root mean square value is that with the primary tonal values removed, i.e. it is a measure of the broadband background vibration.

Compared in Figure 11 to Figure 14 are root mean square values for different cargo bay floor locations and axes. The comparisons are made for the same four selected flight conditions for which power spectral densities are presented in Figure 1 to Figure 4.

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

4.2 Set down of underslung cargo from a Boeing CH-47 rotorcraft

Although the Boeing CH-47 rotorcraft has a significant sized internal cargo area, it is not uncommon to transport bulky items as underslung loads. In such cases the load may be attached by cables or nets to release hooks on the underside of the rotorcraft. Although the Boeing CH-47 rotorcraft has several such release hooks, it is common to utilize a single hook for most single items.

It should be noted that when underslung loads are carried by smaller rotorcraft they may use two, three or even four point attachments. In all cases, it is possible for the dynamic responses of the cargo and its suspension arrangement to interact with the dynamics of the rotorcraft inducing increased dynamic loads in the attachment arrangement and hence the cargo/rotorcraft. It is not unknown for failure of such arrangements to occur during flight.

Following the measurement exercise described in 4.1, further work [2] was undertaken to establish set down shock conditions of underslung loads. For the purpose of this work an air portable ISO container was suspended (at its upper attachments) by four cables to a single point payload release hook under the rotorcraft fuselage. The air portable ISO container was a 10-foot-(3 m) long unit (i.e. half the length of a standard TFU container) holding a two-tonne payload. The pilot instructions were to perform representative set downs of the container. It was set down onto a hard concrete surface, as far as practicable, on its four corner stacking points using "realistic" rotorcraft decent velocities.

The suspended load was instrumented using the same equipment as described in 4.1. However, in this case the two trial-axial accelerometers were located at each of the lower four corners of the air portable ISO container. The system provided an effective measurement frequency range of 2 Hz to 250 Hz with a subsequent acquisition rate of 1 000 samples per second (sps). Measurements were made throughout the set down and the specific event subsequently extracted for shock analysis.

The analysis was in the form of time histories (which are not suitable for reproduction here) and shock response spectra (SRS). The time histories used for the shock response spectrum calculations were of approximately 1 s duration and adopted a resonant gain or Q of 16,66 to facilitate comparison with some historic US data. Although the measurement exercise encompassed twelve separate set downs of the underslung payload, not all of these provided data of suitable quality for subsequent analysis.

Figure 15 show the shock response spectra for six set downs. The figure includes the vertical responses from both instrumented lower corners of the air transportable ISO container. The shock response spectra for six set downs imply that the set down velocities were in the range of approximately 0,2 m/s to 1 m/s. This broadly aligns with broader experience of setting down underslung loads on land or stationary vehicles. The set down velocities would typically be greater when setting down underslung loads onto ships.

Although the information in this document is limited in quantity and frequency range, the quality of the information is reasonable and meets the required validation criteria for data quality (single data item).

4.3 Supplementary data

The supplementary data, detailed below, comprises information arising from reputable sources, but for which the data quality could not be adequately verified.

A study, [3] and [4], was undertaken to identify parameters and methodologies by which estimates could be established of the vibration severities experienced by weapons carried on rotorcraft. Although the objective of this work related to externally carried weapons, it did first need to consider the vibration severities of the rotorcraft itself. The work did not present measured rotorcraft data directly, hence its consideration as supplementary data. However, the work did present information related to parameters which influence vibration severity for several rotorcraft types. Figure 16 to Figure 18 show the relative vibration amplitude at blade passing frequency for different airspeeds (referenced to 100 kn) and for three different rotorcraft i.e. the Lynx, Seaking and Chinook (CH-47). These are respectively small, medium and large rotorcraft. This information indicates that whilst the most severe vibrations occur at the highest speed for the CH-47, that is not necessarily the case for the other types. The study also presented (see Figure 19) aircraft to aircraft variations that occur between different airframes of the Lynx rotorcraft.

Early editions of UK Defence Standard 00-35 [5] presented some of the information from the study [3] and [4] addressed in the preceding paragraph. Later editions have replaced the rotorcraft to rotorcraft information shown here in Figure 19 with more extensive information from a more modern rotorcraft. The data shown in Figure 20 arises from more than a thousand measurements made on 36 different airframes of the same rotorcraft type and build standard. These measurements, made as part of a fleet maintenance activity, are made at the same aircraft reference location (a hard point on the cockpit floor). Although the original measurements were made in terms of vibration amplitude at the blade passing frequency, they have been converted to variations about the average amplitude. The most severe amplitudes are over three times the average amplitude and six times the most benign observed.

The French military standard GAM-EG-13 [6] includes vibration information from the Aerospatiale SA 321 Super Frelon[3] rotorcraft. This is a three-engine heavy lift rotorcraft which is also produced in China where it is known as the Z-8. Power spectral density measurements are presented for three axes and nine flight conditions in Figure 21 to Figure 23 for the X, Y and Z axes respectively. The orientation of the axes and the location of the measurements is unknown but is presumed to be the cargo bay floor with the Z axis vertical. The duration of the measurements used in the analysis and the analysis frequency bandwidth are unknown (although it appears likely that a resolution of better than 1 Hz was adopted). The military standard indicates the rotorcraft take-off weight to be 12 900 kg, the mass on landing to be 12 100 kg and the unladen mass of the rotorcraft to be 7 925 kg. The ten flight conditions are indicated to be: on ground rotor not turning, rolling take-off, stationary ground effect, accelerate to a forward speed of 70 kn, straight and level flight at 85 kn, 110 kn and 130 kn all at a flight level of 500 ft (150 m), as well as deceleration in forward speed followed by transition to hover.

As part of an exercise, in the early 1970s, to authenticate test severities for the US military specification Mil Std 810, J.T. Foley [7] at the US Sandia National Laboratories undertook an extensive exercise to establish transportation severities on a number of platforms including some information on transportation in an (unknown) rotorcraft. Unfortunately, the analysis process used by Foley throughout his work is relatively unique and not directly comparable with the information presented in this document.

The SRETS study (see [8]) was undertaken during 1998 and reviewed both measured data sources and test severities for a variety of methods of transportation. It contained no measured data from transportation in rotorcraft although it did refer to rotorcraft test severities. However, those appear in NATO STANAG 4370 AECTP 400 [10] and as such are already considered within this document.

A number of environmental test standards include test severities for equipment either transported or installed in rotorcraft. These test standards adopt differently shaped random or composite profiles and they are not particularly consistent with respect to amplitude. Moreover, the difference between measured severities and test severities can be quite marked for rotorcraft. Test severities for equipment installed in rotorcraft do tend to have a notably higher amplitude than observed in the measured data. This seems to be because the tests typically encompass installation for the entire life of the rotorcraft airframe. As a consequence such tests often incorporate increased amplitudes to facilitate a degree of accelerated testing. The need for accelerated testing is less important for equipment transported in rotorcraft as exposure to this environment is generally limited to a few hours. This is a consequence of the limited range of a rotorcraft as well as the relatively high cost of this method of transport. For these reasons, it is worthwhile considering the test severities of a number of representative standards.

Over the years the US defence equipment test standard Mil Std 810 [9], has included a number of different vibration test types and severities for equipment transported and installed in rotorcraft. The latest version of this standard uses sinusoidal tones on a shaped random vibration background. The standard sets out separate advice on the vibration severities for equipment transported by rotorcraft and those for equipment installed in rotorcraft. However, in

3 SA 321 Super Frelon is the trade name of a product supplied by Aérospatiale. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named.

reality the two sets of severity guidance are essentially identical. Within each set of guidance four severity levels are provided of which three are very location specific (instrument panel, on or near drive system elements and external stores). A single severity level is used for all the remaining airframe locations and is applicable to both transported and installed equipment. The standard requires that the severities are tailored to a specific rotorcraft type and for that purpose supplies information on main and tail rotor speeds as well as the number of blades on each. Figure 24 shows the vibration test severity derived for the CH-47 rotorcraft using the severity derivation approach set out in Mil Std 810 [9]. It should be noted that for comparison purposes the tone components in Figure 24 have been converted to narrowbands of frequency bandwidth ±5 % of the narrowband centre frequency.

Guidance for establishing initial vibration test severities for rotorcraft are set out in NATO STANAG 4370 AECTP 400:2006 [10] Method 401 Annex D. That annex separately addresses vibration severities for transported equipment and for installed equipment. In this case, the two test severities are different. Figure 25 shows the vibration test severity derived from the approach set out in Method 401 Annex D for equipment transported in the CH-47. Method 401 Annex D also contains vibration test severities for equipment carried as underslung loads carried in both containers and nets (see Figure 26). The vibration test for equipment installed within rotorcraft uses four harmonically related tones which are swept across frequency bands (of 20 Hz, 40 Hz, 60 Hz and 80 Hz respectively for the tones). The width of each of these swept bands approximately relates to the range that may be encountered by a wide range of rotorcraft types. It should be noted that again for comparison purposes the tone components in Figure 36 have been converted to narrowbands of frequency bandwidth ±5 % of the narrowband centre frequency.

The latest UK Def Stan 00-35 [5] environmental test standard for defence equipment contains four vibration test severities for transportation of equipment in rotorcraft. Three of these are for specific rotorcraft types and one is a generic test for underslung loads (although the standard does not include a shock test specifically for set down of loads). Previous issues of this standard included a test for multi-rotorcraft types. However, this has been removed in the latest issue as it was found its severities produced unrealistic test failures. The rotorcraft specific vibration test severities relate to Chinook (CH-47), Merlin and Lynx/Wildcat rotorcraft and are shown in Figure 27, Figure 28 and Figure 29 respectively. The first two types are both large transports but the latter is a small rotorcraft which is included only for man portable equipment. Figure 30 shows the vibration test severity for underslung loads. It should be noted that the standard allows the use of both tones and narrowbands to replicate the blade passing harmonics. The severities for the blade passing harmonics are defined in terms of root mean square values from which narrowband amplitudes may be calculated using multiples of the frequency bandwidth achievable by the vibration test controller. In this case, the amplitude shown in the figures are based upon a narrowband frequency bandwidth of 2 Hz (which is reasonably representative).

US standard RTCA/DO-160 [11] and EUROCAE/ED-14 [12], which are identically worded, are applicable to equipment installed within aircraft and rotorcraft. These standards specify vibration test severities for five different locations within the rotorcraft (fuselage, instrument panel and racks, nacelle and pylon, engine and gearbox as well as the empennage and fin tip). Severities are supplied for both reciprocating and turbo-jet engines rotorcraft. The severities are constructed to allow rotorcraft specific severities to be used as well as generic severities when the rotorcraft blade passing frequencies are unknown. Figure 31 shows the test severities for equipment located in the fuselage of a rotorcraft with known blade passing frequencies, i.e. those for the CH-47. Two severities are supplied, one is used when the performance of equipment is evaluated, the other is the endurance severity used to demonstrate the equipment life. It should be noted that again for comparison purposes the tone components in Figure 31 have been converted to narrowbands of frequency bandwidth ±5 % of the narrowband centre frequency.

5 Intra data source comparison

5.1 General

The purpose of the discussions addressed within Clause 5 is to review each data source for self-consistency.

5.2 Vibration of Boeing CH-47 rotorcraft

The purpose of the vibration measurements on the CH-47 rotorcraft [1] was to supply information for a UK military standard on the vibration environment experienced by cargo transported by rotorcraft. Although the CH-47 rotorcraft did not generate the most severe rotorcraft environment, it was the rotorcraft most likely to be used to transport cargo on land.

At the time that this measurement work was undertaken, a number of national and international standards represented the vibration severities for rotorcraft in a variety of different ways. Many of these were not comparable with the test spectrum typically used to represent transportation by road, rail and other types of aircraft. As a consequence doubt existed as to whether the generic transportation tests, which existed at that time, encompassed transportation within rotorcraft. This doubt was exacerbated because some tests using rotorcraft severities resulted in certain types of container and equipment failures, which were not generated by tests for other types of transport.

The vibration measurements from the cargo bay area of the CH-47 rotorcraft, especially during straight and level flight, did prove to be somewhat lower than expected. It was observed that the most severe vibration conditions occurred during transitory events. Those events occurred, not only for very short periods, but also only occasionally during a typical flight. Also some events, notably transition to autorotation, mostly only occurred in emergencies.

The vibration measurements from the cargo bay area of the CH-47 rotorcraft do illustrate a number of characteristics which seem to be typical of larger (transport) rotorcraft. Figure 1 to Figure 4 illustrate that the vibration spectral responses occurring at blade passing frequency (11,25 Hz in this case) is generally the most severe. The spectral amplitudes of the harmonics of the blade passing frequency progressively decrease in amplitude, but only at a modest rate. As a consequence the amplitudes at even high harmonic orders are still strongly apparent. In some cases, especially for transient events, the vibration responses occurring at the second or third harmonic may be particularly significant. Figure 11 to Figure 14 illustrate that the most severe vibration responses of the cargo bay floor occur in the vertical axis. Moreover, although the vibration severities are indicated to be marginally more severe at the forward end of the cargo bay area, generally the variations along the length of the cargo bay are not that great (for example, compared to the variations observed in propeller aircraft).

The extent of the vibration information, presented in the measurement report on the vibrations in the cargo bay area of the Boeing CH-47 rotorcraft, does have some limitations. Nevertheless, the report does present data which appears to be self consistent and shows trends and values which are largely within expectations. As a consequence the data meets the required validation criteria for quality against the intra data source comparison criteria.

5.3 Set down of underslung cargo from a Boeing CH-47 rotorcraft

The underslung cargo set down shock measurements [2] are the only data of this type reviewed here. Nevertheless, the amplitude and characteristic of the shock response spectra are those that would be expected from the type of event considered here. The shock response spectra illustrated in Figure 15 would not be well represented by a half sine shock pulse. However, the amplitude in the vertical axis could, in part, be represented by a half sine pulse of around 12 *g* with a velocity change corresponding to a value of around 1 m/s.

Overall, the 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.

5.4 Supplementary data

The UK supplementary data from [3], [4] and [5] extend the UK information on the Boeing CH-47 to other rotorcraft. Although this supplementary data largely supports other data, it does suggest the variations in vibration severity with airspeed are more complicated than a simple proportionality relationship. Indeed the supplementary data would suggest the relationship between vibration severity and airspeed, particularly at blade passing frequency, could be aircraft type specific. The UK supplementary data also provides information on the variability of vibration between airframes and changes in vibration over time on the same airframe (although these aspects cannot be separated in the data supplied). Although variability in vibration between airframes and over time is reasonably well known (in that modern rotorcraft airframes are commonly fitted with systems to monitor the vibrations), little real information is published.

The supplementary vibration data from GAM-EG-13 [6] on the Aerospatiale SA 321 Super Frelon rotorcraft is, as far as would be expected, consistent with the measured data from the Boeing CH-47.

Consideration of the information on rotorcraft vibration test severities from different standards [9], [10], [11] and [12], is not strictly within the scope of this series of documents. However, in this case the existing test severities are helpful in that they indicate the factors that have been applied, by different agencies, to accommodate variability between aircraft. The test severities also indicate that those other standards utilize composite vibration testing i.e. using either fixed frequency sinusoidal tones superimposed on broad band random or fixed centre frequency narrowbands superimposed on broad band random.

6 Inter data source comparison

For the most part, the data from the various sources indicated a reasonable degree of self-consistency and agreement across sources. As such the data meets the required validation criteria for quality against the inter data source comparison criteria.

7 Environmental description

7.1 Physical sources producing mechanical vibrations

The primary dynamic excitations affecting equipment transported in rotorcraft arise from the main rotor blades. The excitations from the rotor blades originate from the flow effect, the mechanical vibration emanating from the blades, the engine shaft rotation and the transmission system. For single rotor rotorcraft the tail rotor and its transmission system will also contribute rotational components to the materiel mechanical environment. For dual rotor rotorcraft, significant dynamic responses can occur due to the interaction between the two sets of blades, at twice the blade passing frequency. All of these rotational components appear as a complex interaction of tonal dynamic responses. The aerodynamic flow over the airframe from flight and from the downwash of the rotor blades, also contributes to the overall mechanical dynamic response in the form of a broadband dynamic response. The dynamic response at any point on a rotary wing aircraft will be the sum of several sources and excitation mechanisms.

A description of the main sources of mechanical vibration on rotary wing aircraft and the mechanisms producing them are set out below.

a) Direct mechanical excitation from the main rotor: The vibration from this source produces the largest low frequency dynamic excitation component. In addition, it also produces the largest dynamic response displacement amplitudes. The cause of this dynamic excitation is the change of the angle of incidence of each blade as the helicopter advances through the air, dynamically exciting the blade. This process is controlled by the application of cyclic pitch and results in large periodic forces at the rotor hub.

b) Indirect excitation from the rotor blades: The rotating rotor blades produce an acoustic pressure field which can excite the aircraft structure. The resultant dynamic responses of the structure occur at a higher frequency than the preceding source. The excitation of the structural modes of the airframe is generally low, due to relatively inefficient coupling with the structure.

c) Vibrations arising from the gearbox: The gearbox is an important source of vibration within a helicopter. Vibrations arise as a result of fluctuating forces within the gearbox and gear mesh interactions.

d) Vibrations arising from the tail rotor: The tail rotor usually produces lower level dynamic excitation than the main rotor. However, in a limited number of cases, interaction can occur between the tail and main rotors producing a characteristic noise.

e) Vibrations arising from installed equipment: Numerous items of installed equipment can cause extraneous dynamic excitations. Their magnitude will depend largely on the distance of the payload from the excitation source.

As already observed, significant vibration responses occur at the main rotor blade passing frequency, which is apparent at low frequency. A notation system has evolved for describing the various rotational frequencies. If R is the rotational speed of the rotor and n is the number of blades on the main rotor, then the blade passing frequency is given by nR, and the subsequent harmonics are $2nR$, $3\ nR$, etc. Similarly, for the tail rotor, blade passing frequencies are denoted by nT, $2nT$, etc., where T is the rotational speed of the tail rotor and n denotes the number of blades. Typical structural dynamic excitation frequencies and their sources are shown in Table 1.

Table 1 – Typical structural dynamic excitation frequencies and their source

Source	**Frequency range** (Hz)
Ride motions, effects of turbulence	0 to 3
Main rotor (R)	3 to 7
Fuselage bending modes	5 to 8
Rigid body modes of external stores on their carriers	6 to 20
Main rotor blade passing (nR)	10 to 25
Tail rotor (T), multiples of (nR), tail drive shaft, pumps, gearboxes	20 to 80
Tail rotor blade passing (nT), pumps, engines and gearbox, output shafts	80 to 160
Main gearbox tooth meshing	450 to 700
Hydraulic pump piston frequencies	500 to 1 000
Further gearbox tooth meshing frequencies	700 to 10 000
Engine turbine blades passing	10 000 plus

The main rotors are normally driven at a constant speed, as a consequence a single rotorcraft type will have a vibration frequency response characteristic related to the rotor speed and the number of rotor blades. This frequency response characteristic will occur largely regardless of flight condition, although the response amplitudes will vary. The rotor speed and number of rotor blades is generally well known for a particular rotorcraft type. As a consequence the blade passing frequency can easily be determined for most rotorcraft types. Typically, the blade passing frequency will be in the 10 Hz to 25 Hz region. Although traditional designs of tail rotor will have a tail rotor blade passing frequency in the 80 Hz to 160 Hz region, some modern designs may have tail blade passing frequencies as high as 4 000 Hz.

The excitation sources, associated with rotary wing aircraft, typically produce vibrations of a complex nature. Moreover, the flight conditions producing the worst case vibration severities vary with aircraft type. Nevertheless, the worst case vibration severities mostly occur during transient flight conditions and manoeuvres. Such transient flight conditions include transition to hover, transition to and from auto-rotation and in-ground hover and flight. Of these the transition to hover from forward flight manoeuvre is commonly the most severe flight condition. The vibration severities arising from transient flight conditions typically exceed, by a significant margin, those occurring during steady state straight and level flight. Additionally, the vibration severities, occurring during straight and level flight conditions, do not necessarily follow a simple relationship with air speed. This is because at some flight speeds (and particularly at higher flight speeds) an advancing rotor blade may encounter turbulent air from the preceding blade. Also, due to the rotational direction of the main rotor, turns to port or starboard may produce different vibration responses for otherwise similar flight conditions.

The position of materiel within a rotorcraft does influence the dynamic environmental conditions, however not to a significant extent. The location of the worst case dynamic conditions is likely to be dependent upon the aircraft type. The airframe of all rotorcraft types is of a relatively light weight construction. As a consequence, the dynamic response can be influenced by the mass and footprint of the attached equipment. Similarly, there is no clear distinction between the vibration response amplitudes in the different axes, although the greatest tonal dynamic response levels on cargo bay floors tend to be in the vertical axis.

At rotor, engine and gearbox locations the dynamic responses will be predominantly influenced by the mechanical inputs from these components. In some cases, active vibration suppression systems are installed between the excitation source and the airframe, which will modify the vibration responses of the airframe. Active vibration suppression systems are usually employed to improve aircrew/passenger comfort and as a consequence mostly operate at lower frequencies. Generally, active vibration suppression systems will supress vibration responses at blade passing frequency and possibly a few subsequent harmonics.

Generally, it can be considered that the greater the payload mass carried by the rotorcraft, the greater the vibration level response. This is because of the increased demand from the power sources during high demand flight conditions, such as take-off.

Unlike fixed wing aircraft, the vibration responses of a rotary wing aircraft can be quite sensitive to the maintenance condition of the rotors, rotor drive and engine systems. Moreover, quite significant changes in the vibration response environment can occur during the life of a particular airframe. In particular, the vibration severity of a particular rotorcraft is known to depend significantly upon its state of rotor track and balance. For this reason, rotor track and balance measurements are commonly taken either during the course of an airframes lifetime or by a continuously operating health and usage monitoring system (HUMS).

The data shown in Figure 20 arises from more than a thousand measurements made on 36 different airframes of the same rotorcraft type and build standard. These measurements, made as part of a fleet maintenance activity, are made at the same aircraft reference location (a hard point on the cockpit floor). Although the original measurements were made in terms of vibration amplitude at the blade passing frequency, they have been converted to variations about the average amplitude. As can be seen, the distribution of amplitudes approximates to a Gaussian distribution. The most severe amplitudes are over three times the average amplitude and six times the most benign observed.

7.2 Environmental characteristics and severities

The vibration responses experienced by equipment transported within rotorcraft are generally characterised as Gaussian broadband random motions, with superimposed periodic tonal components. A typical rotorcraft vibration response spectrum is dominated by tonal peaks at the main rotor blade passing frequency and its associated harmonics. The broadband random element arises from both aerodynamic and power plant sources. The relatively light weight construction of rotorcraft cargo bay floors can produce responses apparent in the broadband random spectral characteristics.

Historically, the vibration responses experienced by equipment installed within the rotorcraft were defined in terms of sinusoidal severities. These severities enveloped the tonal components arising at the blade passing frequency and its harmonics. Typically the sinusoidal response envelope was defined as a constant displacement amplitude from 5 Hz to around 20 Hz above which it would be defined as a constant acceleration amplitude. Such an envelope has the advantage that it could encompass a range of different rotorcraft types, i.e. with different blade passing frequencies. The main disadvantage was that the sinusoidal response envelope usually represented a far more severe condition than was actually experienced by a single rotorcraft type. Another issue with this type of description arose when it was converted into a test severity. Representing the sinusoidal response envelope as a sine sweep test would not necessarily create the same fatigue damage, at the blade passing frequency and its harmonics, as actually occurs. For this reason the sinusoidal response envelope was typically represented by a mix of sine sweep and sine dwell tests. Today few extant specifications use the sinusoidal response envelope as a means of defining the rotorcraft vibration environment. However, for some older rotorcraft designs it is not uncommon to find such a definition in the requirements for installed equipment.

The approach used by most current specifications for equipment installed or transported within rotorcraft use a definition based upon broadband random vibrations, with superimposed periodic tonal components. Some specifications utilize narrowbands to represent and quantify the periodic components, others use sinusoidal components.

As previously indicated, the engine/transmission/rotor of a rotorcraft are mostly fixed speed. Although some small variations in speed can arise when an aerodynamic load is suddenly applied to the engine/transmission/rotor assembly, for the vast majority of a flight the speed is constant and variations are small.

When setting a rotorcraft vibration severity from measured data, it should be noted that the spectral amplitude (in g^2/Hz) of the tonal components on an acceleration power spectral density arising from rotors is dependent upon the analyser's resolution and therefore should not be used quantitatively. It is generally considered to be a more accurate approach to quantify the periodic components as sinusoidal components, i.e. by their root mean square values. If narrowband components need to be used for testing purposes, the conversion from sinusoidal amplitudes to narrowband amplitudes should only be made after the actual frequency bandwidth of the vibration test control system is known and can be used in the conversion calculation. This is because the typical frequency bandwidth of the vibration test control system may only be one tenth that of the blade passing frequency. As a consequence small differences in the frequency bandwidth which may occur between different vibration test control systems can have a significant effect on conversion from sinusoidal amplitudes to narrowband amplitudes.

7.3 Derived test severities

The type of vibration test severity adopted to represent the conditions within rotorcraft, have varied somewhat over the years. Historically, the test type adopted (typically a sinusoidal sweep/dwell test) arose due to the lack of test facilities able to reproduce actual conditions. However, it was also partly to facilitate a single test which encompassed a range of rotorcraft types. The effect of the rotors is to introduce significant tonal components the frequency of which may be unique to a particular aircraft type. From the viewpoint of mechanical vibration testing, the test specifier has a choice of either considering each rotorcraft variant separately or attempting to generate a test which encompasses all likely rotorcraft variants. The latter can have the disadvantage that the resultant test severity can be far more severe than would be experienced on any single rotorcraft type considered.

The broadband random components of rotorcraft vibration are relatively low and can be easily encompassed with a conventional broadband random vibration test schedule. However, this situation is not so easily addressed for the tonal components. If these tones are to be included within a conventional broadband random vibration test, then high amplitudes are needed to encompass them. Attempting to utilize such amplitudes across the entire test frequency range clearly increases the overall vibration root mean square to a very high degree.

A more usual approach is to utilize either a shaped broadband random vibration test severity or a composite vibration test. The former option typically adopts a test procedure such as that set out in IEC 60068-2-64, Test Fh [13]. This still increases the overall vibration root mean square but not to such a significant extent as attempting to envelope the entire test. This approach is in use by many specifications setting out rotorcraft vibration test requirements because it can be undertaken at a wide range of test facilities. The composite vibration test approach, such as that set out in IEC 60068-2-80, Test Fi [14], superimposes either narrowbands or sinusoidal tones onto a broadband background random vibration. This allows the test severity to more closely shape the vibration profile around the tones for a single rotorcraft. This approach is also used by many specifications setting out rotorcraft vibration test requirements. Whilst facilities to undertake such tests are becoming more widely available, in some locations this type of test may not be economically viable.

The above notwithstanding, neither the shaped broadband random vibration test severity nor the composite vibration test are consistent with existing severities of IEC 60068 (all parts) [15] or IEC 60721 (all parts) [16]. However, as indicated, a suitable test procedure is available in IEC 60068-2-80,Test Fi [14].

Rotorcraft vibration severities are not specifically specified in IEC 60721 (all parts) [16]. However, it does contain both random and sinusoidal descriptions of vibration conditions for transportation. As already indicated the use of a sine sweep/dwell test to replicate rotorcraft vibration has been adopted historically, but has not found favour for some years. In this case a sine sweep is likely to be less representative than a narrow band random test. Traditionally, the random and sinusoidal descriptions contained in IEC 60721 (all parts) [16] are considered alternative descriptions.

Creating a rotorcraft vibration test severity, from the environmental severities presented in this document requires the inclusion of appropriate test factors or margins, as well as establishing an appropriate test duration. General considerations, relating to both these aspects, are outside the scope of this document. However, rotorcraft do introduce some additional specific considerations which are worthy of note here.

a) When setting appropriate test factors or margins, for rotorcraft vibration tests, the potential variability of vibration severities occurring; between aircraft types, between airframes as well as the change of vibration severity over time, need to be considered. Some information on this was provided earlier in 7.1.

b) When setting test durations, the occurrence of the most severe rotorcraft vibration amplitudes arising as a consequence of transient conditions, needs to be considered. If the test severities are based upon the most severe amplitudes, the test duration may only need to be relatively short to ensure a similar level of equivalent fatigue damage. Specific procedures to establish the test durations for rotorcraft vibration testing have been developed (NATO STANAG 4370 AECTP 2410 and DEF STAN 00-035 Issue 5 Part 5 Chapter 12-01), although a number of other more general procedures can also be adopted. In either case it may be necessary to consider the flight usage of the rotorcraft when setting test durations.

8 Comparison with IEC 60721 (all parts) [16]

The purpose of Clause 8 is to compare the severities identified within this document with those set out in IEC 60721 (all parts). To ensure consistency with the previous documents in IEC TR 62131 (all parts) [21], [22], [23], [24] and [25], this comparison is specifically undertaken using the severities set out in IEC 60721-3-2:1997 [17]. As a result of the comparisons undertaken within the IEC TR 62131 (all parts), IEC 60721-3-2:1997 [17] is to be updated with new categories and severities. These changes are not addressed within this document, but will be addressed in a separate document.

No environmental test severities exist in IEC 60721 (all parts) [16] specifically related to transportation in rotorcraft conditions. Rather the shock and vibration conditions are assumed to be encompassed by those from general transportation. This is also intrinsically the case for the test severities of IEC 60068 (all parts) [15].

The three "transport" categories set out in IEC 60721-3-2:1997 [17] 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 IEC 60721-3-2:1997 [17], 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 [17], Table 5 (2M1, 2M2 and 2M3) apply to four environmental parameters;

– category a) – stationary vibration sinusoidal, (illustrated in Figure 34),
– category b) – stationary vibration random (illustrated in Figure 32),
– category c) – non-stationary vibration including shock (illustrated in Figure 36),
– category d) – steady state acceleration (not illustrated but 2,0 *g* for all categories).

Some years ago it was identified that the amplitudes of IEC 60721-3 (all parts) differed from those of IEC 60068-2 (all parts). 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 TR 60721-4-2:2001 [18]. For the stationary random vibration condition, IEC TR 60721-4-2:2001 [18] recommends the amplitudes of IEC 60068-2-64:1995 (see [13] and illustrated in Figure 33). For the stationary sinusoidal vibration condition, IEC TR 60721-4-2:2001 [18] recommends the amplitudes illustrated in Figure 35. With regard to shocks; the nearest identified severity was that of IEC 60068-2-27:1993, Ea shock (see [19] and illustrated in Figure 35) but the recommended severity was that of IEC 60068-2-29:1987 Eb bump (see [20] and illustrated in Figure 37). Since the recommendations of IEC TR 60721-4-2:2001 [18] were published, IEC 60068-2-29:1987 [20], Eb bump has been merged with IEC 60068-2-27:2009 [19], Ea shock. Nevertheless, for consistency with the recommendations of IEC TR 60721-4-2:2001 [18], IEC 60068-2-29:1987 [20], 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.

The acceleration power spectral densities from IEC 60721-3-2:1997 [17] are compared with the corresponding measured vibrations in Figure 39 to Figure 42. These overlaid comparisons include all the available vibration information from the Boeing CH-47 (Figure 39) and the Super Frelon flight measurements (Figure 40 to Figure 41).

The overlaid power spectral densities from the Boeing CH-47 (Figure 39) are examples of the conditions occurring from four flight conditions. Other data presented in this document suggest these are some of the most severe conditions and arise from the most severe location and axis. Nevertheless the overlaid power spectral densities may not represent the most severe condition that can arise as it is not possible to place these measurements within the distribution of variations that arise from the maintenance state of the rotorcraft. Additionally, the frequency resolution of the data analysis used in this case may not necessarily give rise to the highest power spectral density amplitudes at the blade passing frequency or its harmonics.

It will be seen that the measured severities for the Boeing CH-47 (Figure 39) are well below the severities of IEC 60721-3-2:1997 [17]. However, the peak amplitudes of the blade passing components are marginally less than the 2M1 and 2M2 category severities, but are well below those for the 2M3 category. In this case the frequency analysis bandwidths used were all around 2,5 Hz which is a little wider than would be used in a random vibration test today. A more typical random vibration test bandwidth today would be closer to 1,5 Hz. If the original data had been analysed with such a bandwidth then, assuming the tonal components are sinusoidal, the tonal amplitudes would be around double those indicated.

The peak amplitudes of the blade passing tonal component for the Boeing CH-47 can also be compared with the stationary vibration sinusoidal severities of IEC 60721-3-2:1997 [17]. In this case the severities presented in Figure 5 to Figure 10 can be compared with the stationary vibration sinusoidal severities of IEC 60721-3-2:1997 [17] (Figure 34). However, in undertaking this comparison it should be remembered that the severities presented in Figure 5 to Figure 10 are root mean square values whilst those in Figure 34 are peak values (and are consequently one time greater). On that basis the most severe component indicated in Figure 5 to Figure 10 is due to blade passing during autorotation (with a root mean square amplitude of 0,7 *g*) and is almost exactly the same as the corresponding amplitude in Figure 34 for the 2M1 and 2M2 categories (with a peak amplitude of 1 *g*). The most severe component indicated is exceeded by the severity for the 2M3 category by a margin of 2. It needs to be observed that the random and sinusoidal descriptions contained in IEC 60721-3-2:1997 [17] are historic alternative descriptions and there is no implication that testing using both random and sinusoidal severities is necessary.

The overlaid power spectral densities from the Super Frelon rotorcraft are examples of the conditions occurring from nine flight conditions. Again the overlaid power spectral densities may not represent the most severe condition that can arise as it is not possible to place these measurements within the distribution of variations that arise from the maintenance state of the rotorcraft. The frequency resolution of the data analysis used in this case is not known and it may not be sufficient to give rise to the highest power spectral density amplitudes at the blade passing frequency or its harmonics.

It will be seen from Figure 40 to Figure 42, that the measured vibration amplitudes for the Super Frelon rotorcraft are mostly well below the severities of IEC 60721-3-2:1997 [17]. However, the peak amplitudes of the blade passing component are only marginally less than the 2M1 and 2M2 category severities for the X axis and exceed them in the Z axis. The peak amplitudes of the blade passing component have essentially the same severity as the 2M3 category. In this case the frequency analysis bandwidths used appear to be less than 1 Hz which is about that which would typically be used in a random vibration test.

Although the measured vibration severities presented in this document do not appear to significantly exceed the severities of IEC 60721-3-2:1997 [17], it should be noted that the measurements do not incorporate any margins for measurement error, uncertainty or variations between rotorcraft. It is worthy of note that (with the exception of underslung loads) all the vibration test severities for equipment transported by rotorcraft reviewed within this document have components which significantly exceed the severities of IEC 60721-3-2:1997 [17] (see Figure 43 to Figure 46). In some cases the test severities relating to blade passing frequencies and some harmonics, exceed the measured severities by margins of over 20 times on power spectral density amplitude or around 13 dB. Typically, test severities margins of around 3 dB to 6 dB are utilized to encompass measurement, testing and material variations. Such a large margin in this case would appear to indicate that margins, of between 6 dB and 10 dB have been used to accommodate variations between aircraft. These values would seem to align with the information of Figure 20, which would suggest the need for a margin of a little under 6 dB to encompass the most severe condition if the vibration measurement severities are "average" and up to 10 dB if the vibration measurement severities are at the lower end of the distribution.

Compared in Figure 47 are test severities for underslung loads compared with the severities of IEC 60721-3-2:1997 [17]. The comparison indicates that the severities of IEC 60721-3-2:1997 [17] easily exceed specified test severities for underslung loads. With that said, the conditions experienced by loads underslung on rotorcraft can vary depending on the methods of attachment and the occurrence of dynamic interaction between the payload and the dynamic flight characteristics of the rotorcraft. The loss of underslung loads due to excessive dynamic interaction loads on the suspension cable system on rotorcraft is not unknown.

The shock response spectra severities from IEC 60721-3-2:1997 [17] and IEC TR 60721-4-2:2001 [18] (half sine shock pulse) can be compared with the measured set down shock for an air transportable ISO underslung on the Boeing CH-47 (Figure 48). The overlaid shock response spectra indicate the peak amplitudes of the measured set down shocks are less than those of the two severities for the 2M3 category, but only just in one case. However, the measured set down shocks do exceed that for the 2M1 category and both severities for the 2M2 category.

9 Recommendations

Although a number of measurement exercises have been undertaken on rotorcraft, many of these are not applicable to the purposes of this document. In particular only rotorcraft credibly likely to transport electrotechnical equipment have been considered. This criterion excludes most small rotorcraft which would not generally be used for the transport of goods. Additionally many vibration measurements in rotorcraft are undertaken to establish conditions that may affect the human body (of crew or passengers). Mostly such measurements are restricted to quite low frequencies and are of little value to the purposes of this document. With that said, good data have been identified from a modest number of sources, which encompass a representative transport rotorcraft.

The vibration data from the various sources indicate a good degree of self-consistency and also a reasonable degree of consistency across the various sources. None of the data sources are so obviously significantly different from the remainder, to question the validity of the comparison exercise. It is clear from the information reviewed that the characteristic of the rotorcraft vibrations varies with flight condition, aircraft type and maintenance state of the rotor, transmission and engines. Generally the most severe cargo bay vibrations occur during transient flight manoeuvres which may occur only for brief periods in a typical flight. Moreover, some conditions may only occur in emergency situations or during crew training. During the normal, long duration flight, the most severe vibration conditions that electrotechnical equipment would experience during transportation, usually arise at the highest flight speed. Although the most severe vibration conditions generally arise at lower altitudes, the effect of altitude is not that significant. The exception would be when the rotorcraft is operating very close to the ground. Typically, the greater the rotorcraft payload the more severe the vibration conditions. These aspects notwithstanding, vibration levels will commonly vary depending upon the maintenance state of the rotor, transmission and engines. Such conditions are frequently monitored either by means of continuous HUMS, specific intermittent measurements or by pilot reports.

The most severe blade passing tones of rotorcraft vibrations occur for protracted periods at low frequencies. Those low frequency excitations have the potential to generate significant relative displacements which can result in a number of types of degradation and failure not encountered with other methods of transportation. Such conditions can be exacerbated if the low frequency excitations coincide with the lower modes of natural vibration of packaged electrotechnical equipment. Such coincidence is not uncommon especially if the packaging is primarily designed to minimize vibration and shock from road transportation. In such cases the lower modes of natural vibration of packaged electrotechnical equipment would typically be set to occur slightly above the primary road vehicle suspension modes. That typically puts the lower modes of natural vibration of packaged electrotechnical equipment close to the blade passing tones of rotorcraft.

Damage to packages and packaged equipment can often occur, during rotorcraft vibration testing, when the equipment packaged response modes are lightly damped. In such cases rotorcraft vibration excitations have the potential to cause build-up responses to significant levels. Additionally, some care may need to be taken to ensure packages are able to accommodate the large internal displacements of the equipment that can occur during rotorcraft vibration testing. The damping of well-designed packaging should have the ability to limit the amplitude of such excitations (to typically less than to five times the excitation). However, a poorly-designed package (with low damping and/or adequate internal clearances) may well produce equipment responses significantly in excess of five times the excitation. In such cases damage to the packaged electrotechnical equipment may result.

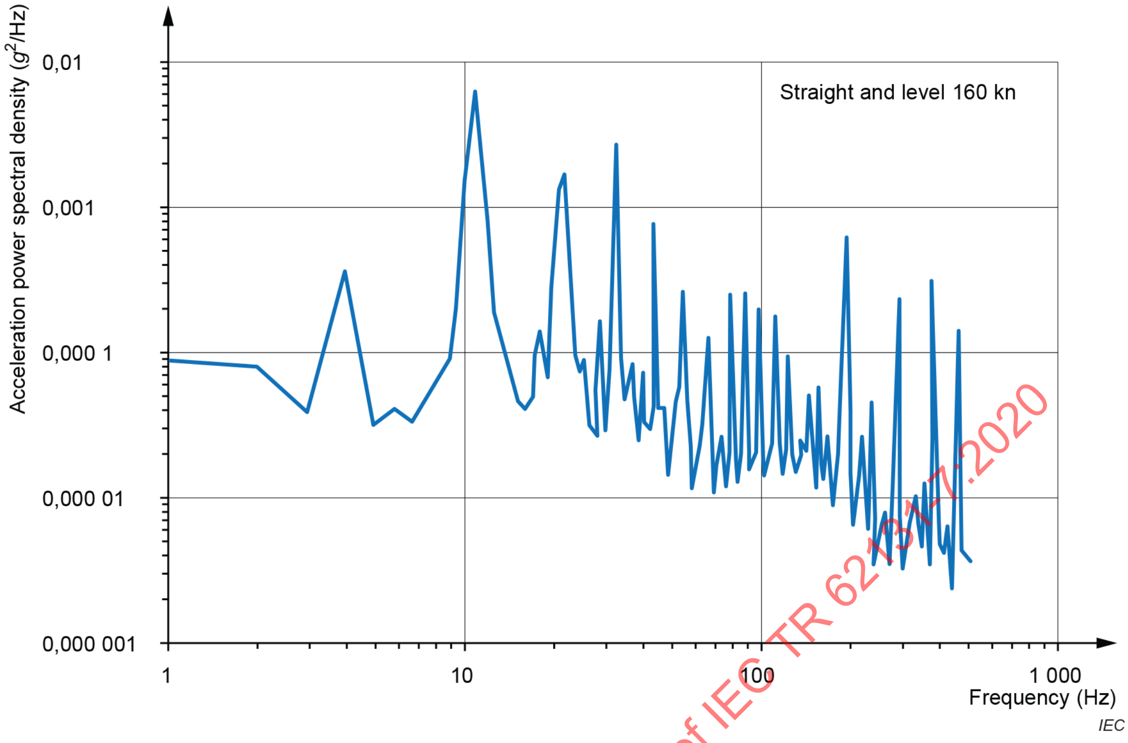

Figure 1 – Typical vibration spectra for CH-47 rotorcraft during straight and level flight at 160 kn [1]

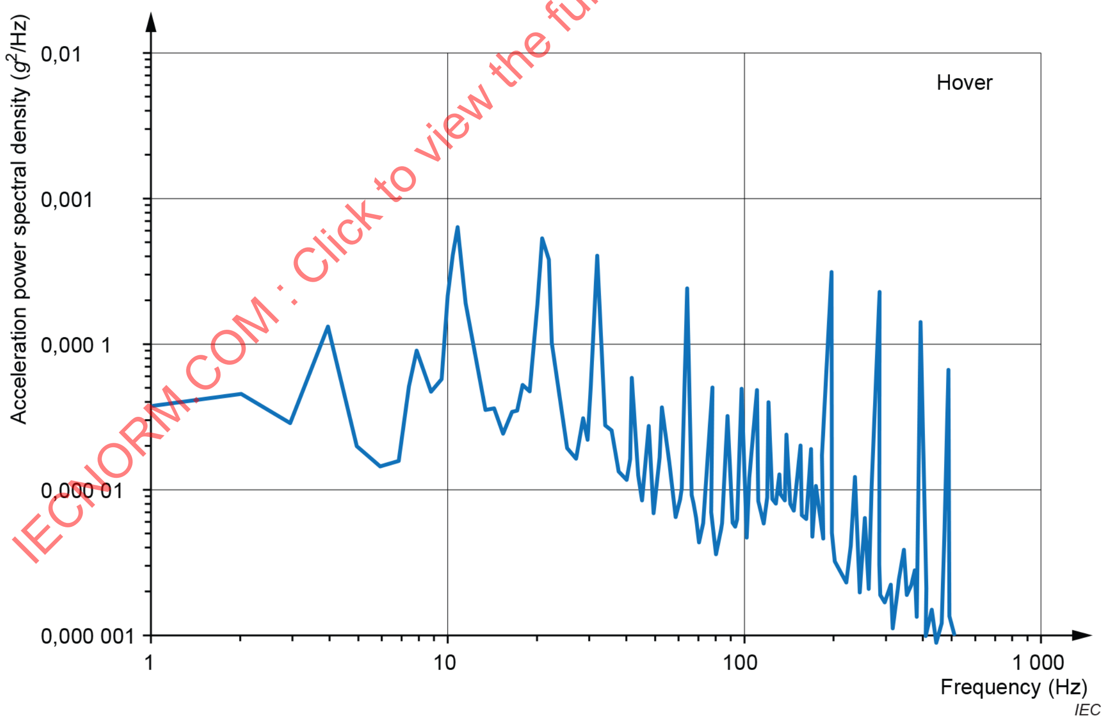

Figure 2 – Typical vibration spectra for CH-47 rotorcraft during hover [1]

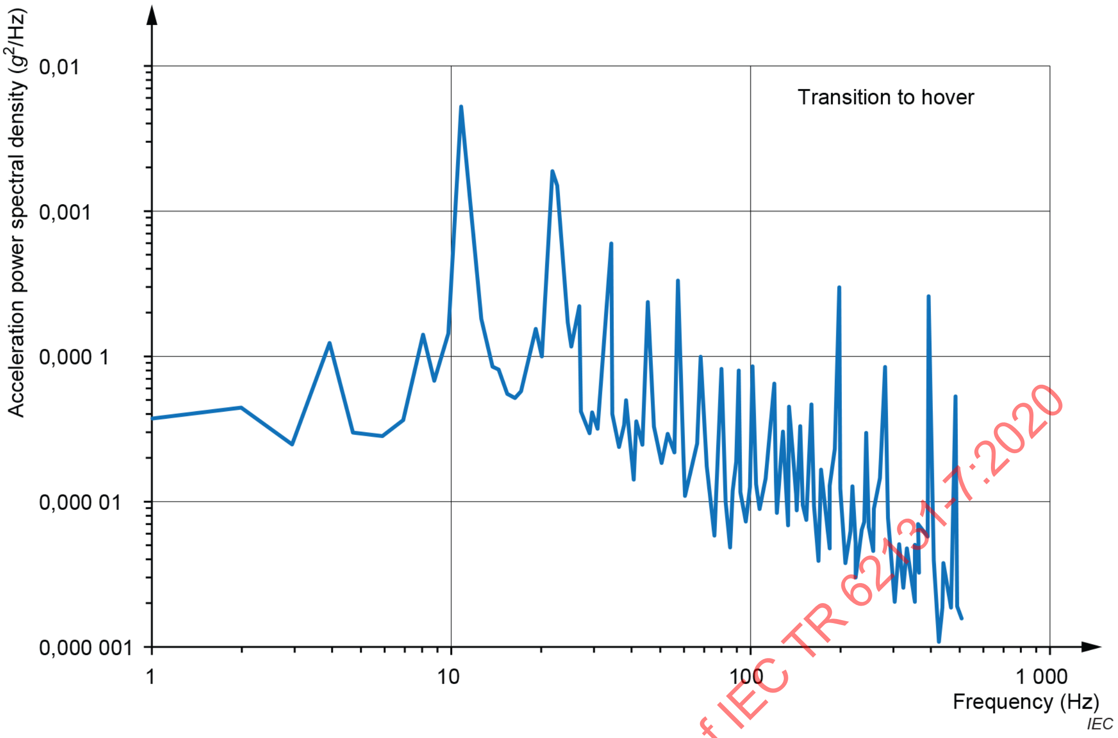

Figure 3 – Typical vibration spectra for CH-47 rotorcraft during transition to hover [1]

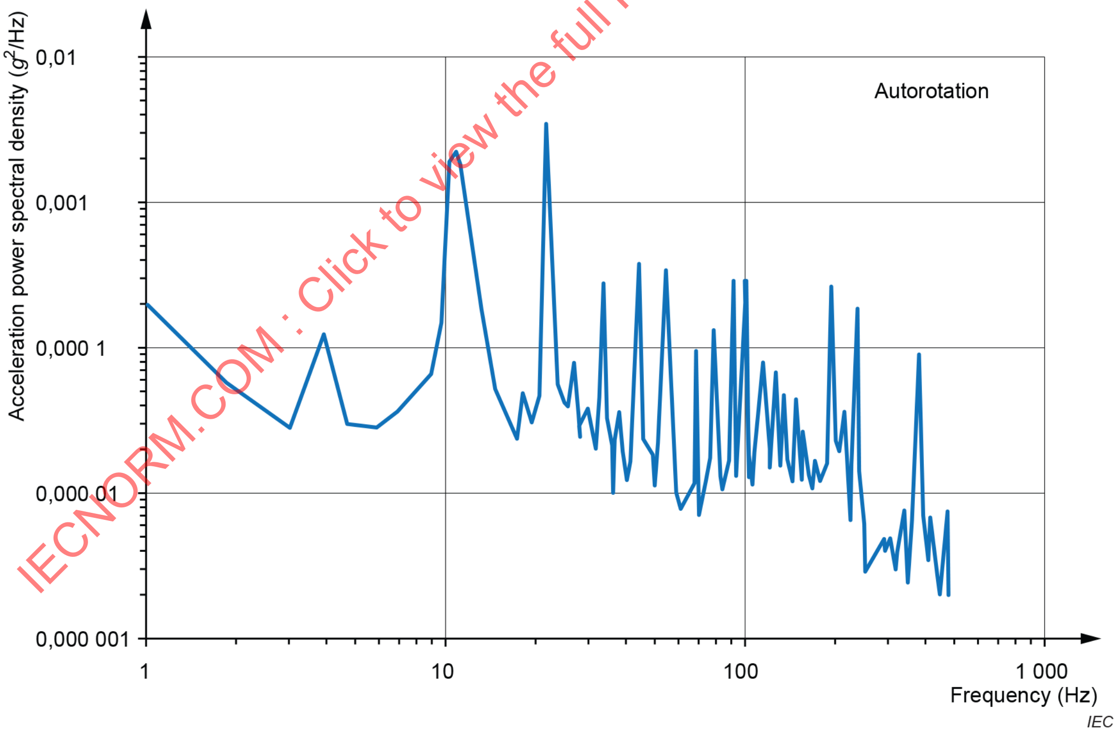

Figure 4 – Typical vibration spectra for CH-47 rotorcraft during autorotation [1]

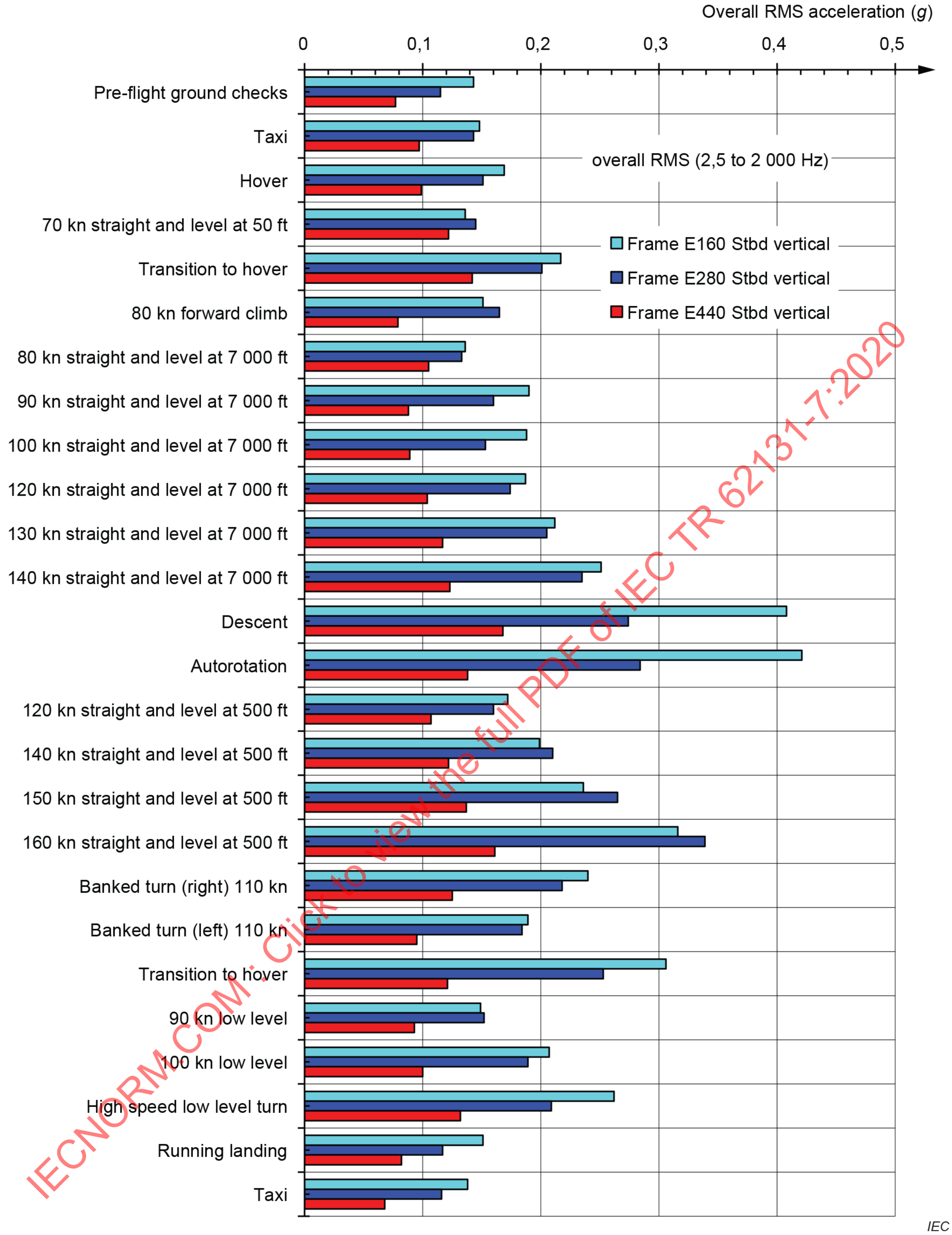

Figure 5 – Comparison of CH-47 vibration overall RMS for different flight conditions [1]

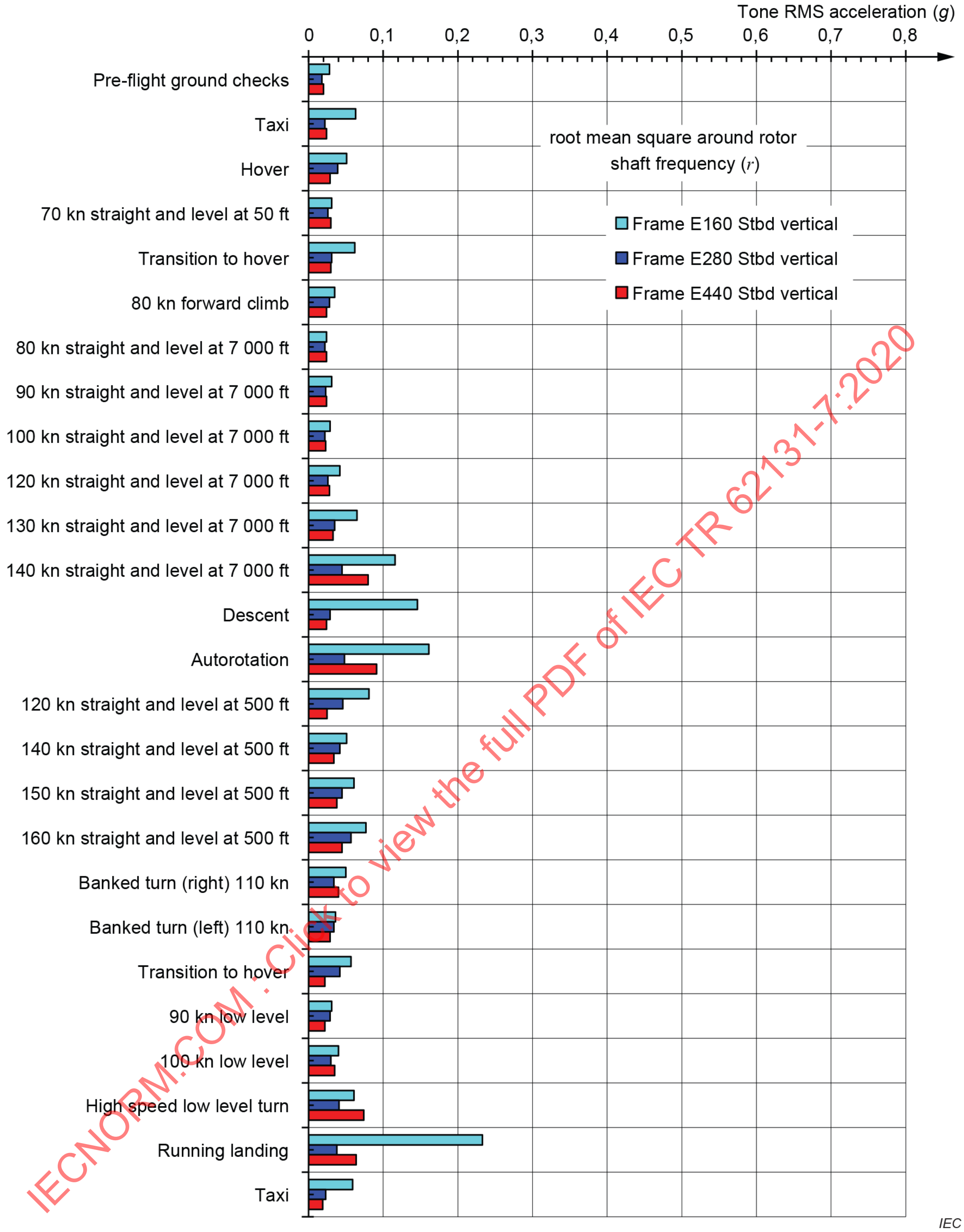

Figure 6 – Comparison of CH-47 vibration RMS severities at rotor shaft frequency (*r*) for different flight conditions [1]

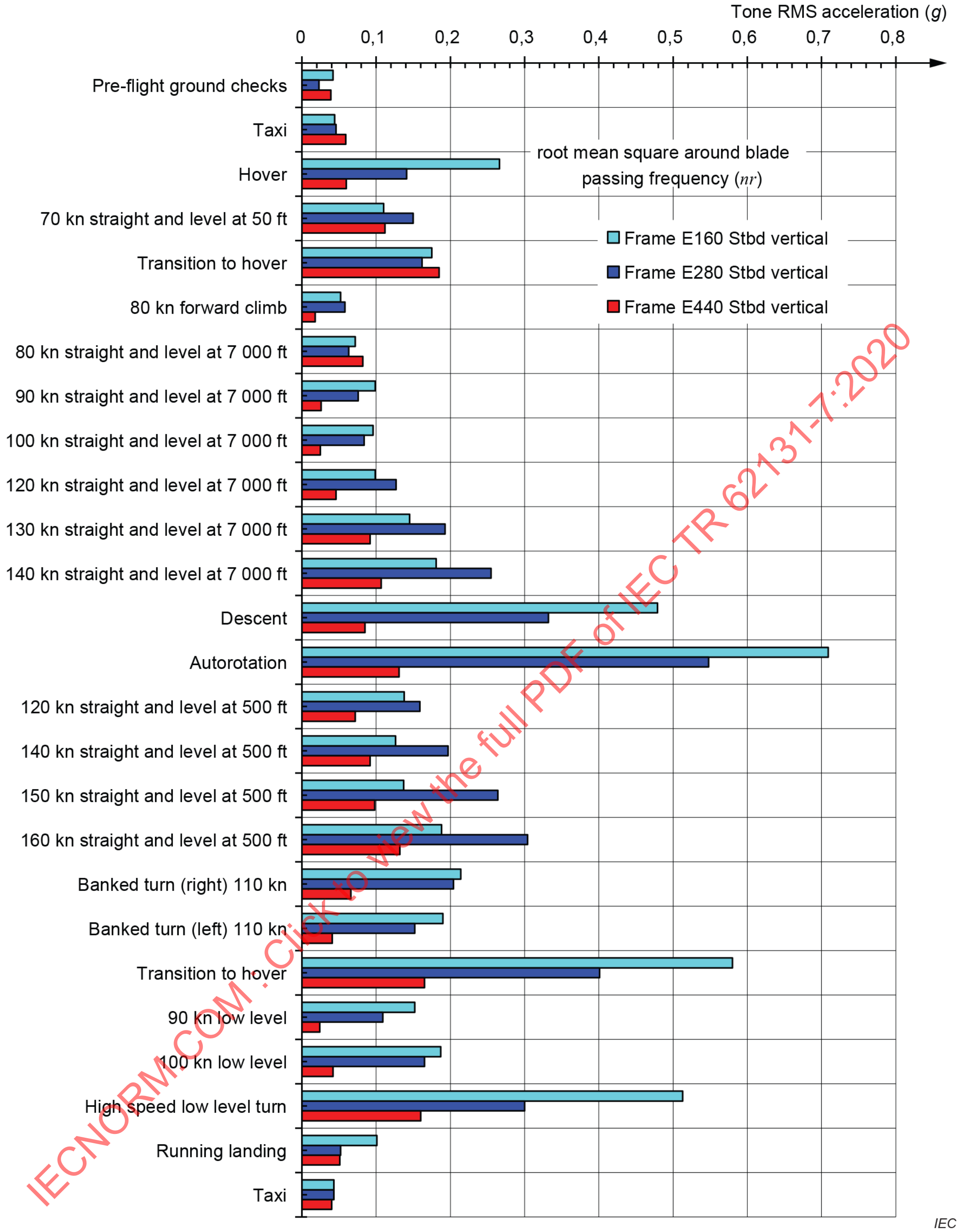

Figure 7 – Comparison of CH-47 vibration RMS severities at rotor blade passing frequency (nr) for different flight conditions [1]

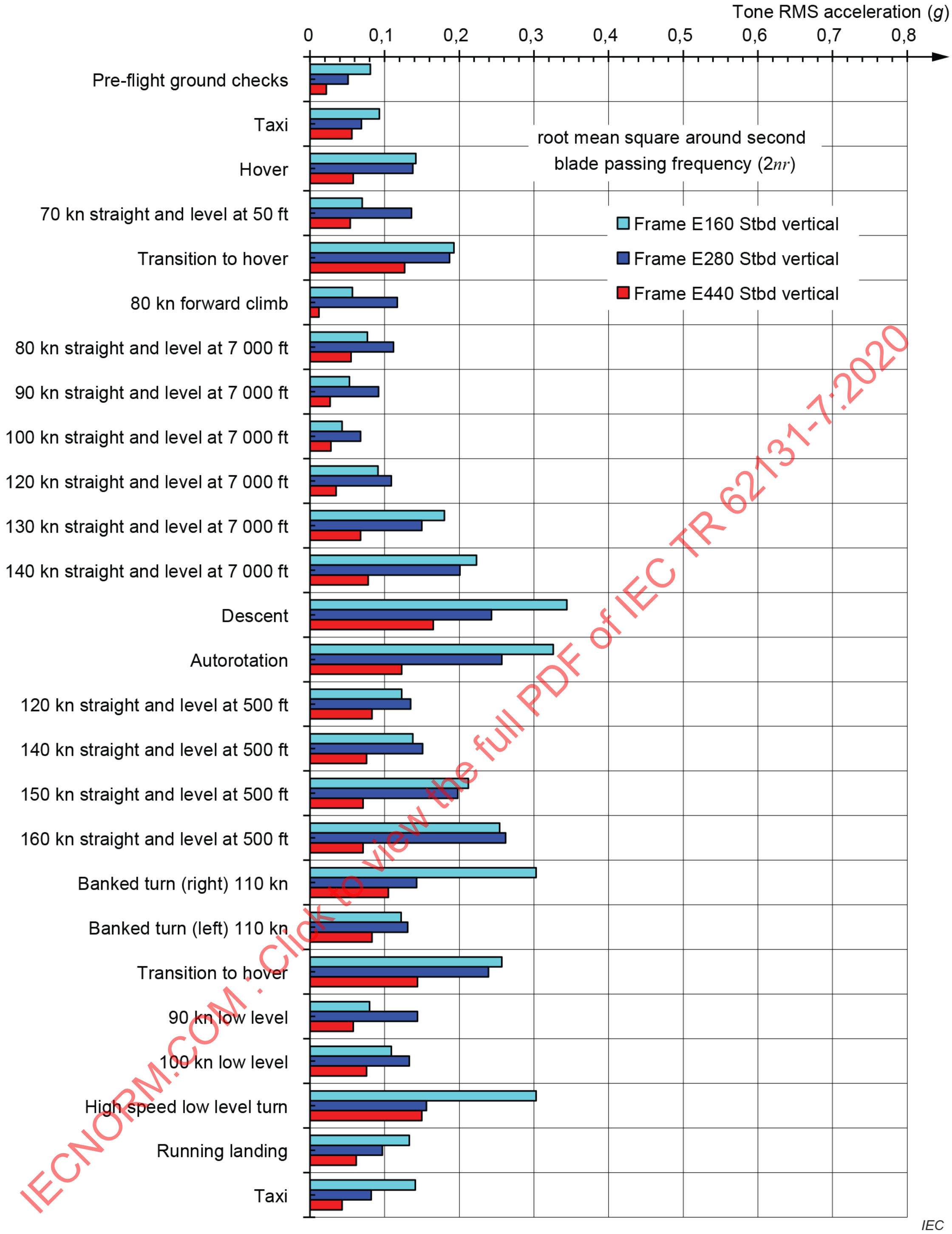

Figure 8 – Comparison of CH-47 vibration RMS severities at second rotor blade passing frequency (2*nr*) for different flight conditions [1]

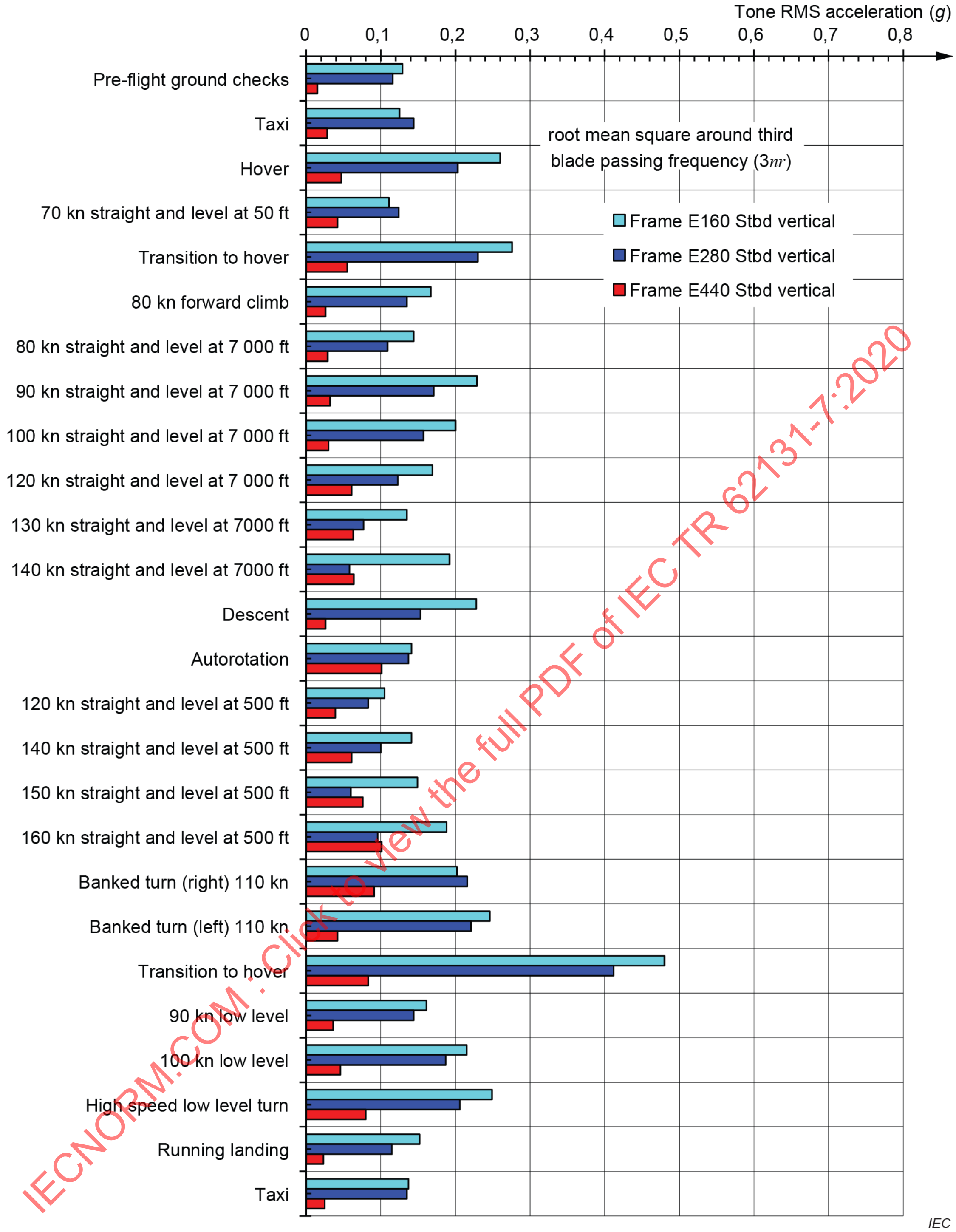

Figure 9 – Comparison of CH-47 vibration RMS severities at third rotor blade passing frequency (3*nr*) for different flight conditions [1]

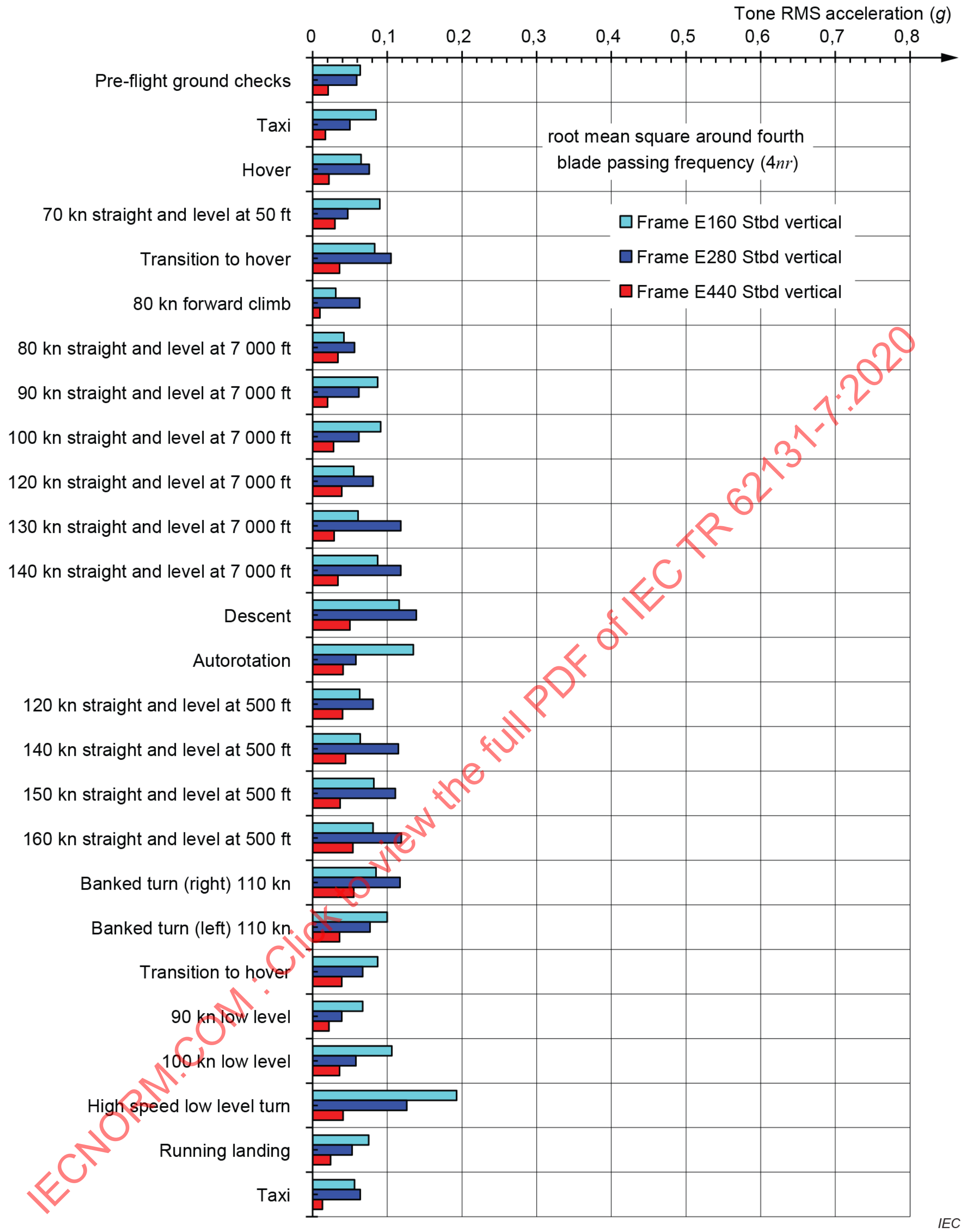

Figure 10 – Comparison of CH-47 vibration RMS severities at fourth rotor blade passing frequency (4*nr*) for different flight conditions [1]

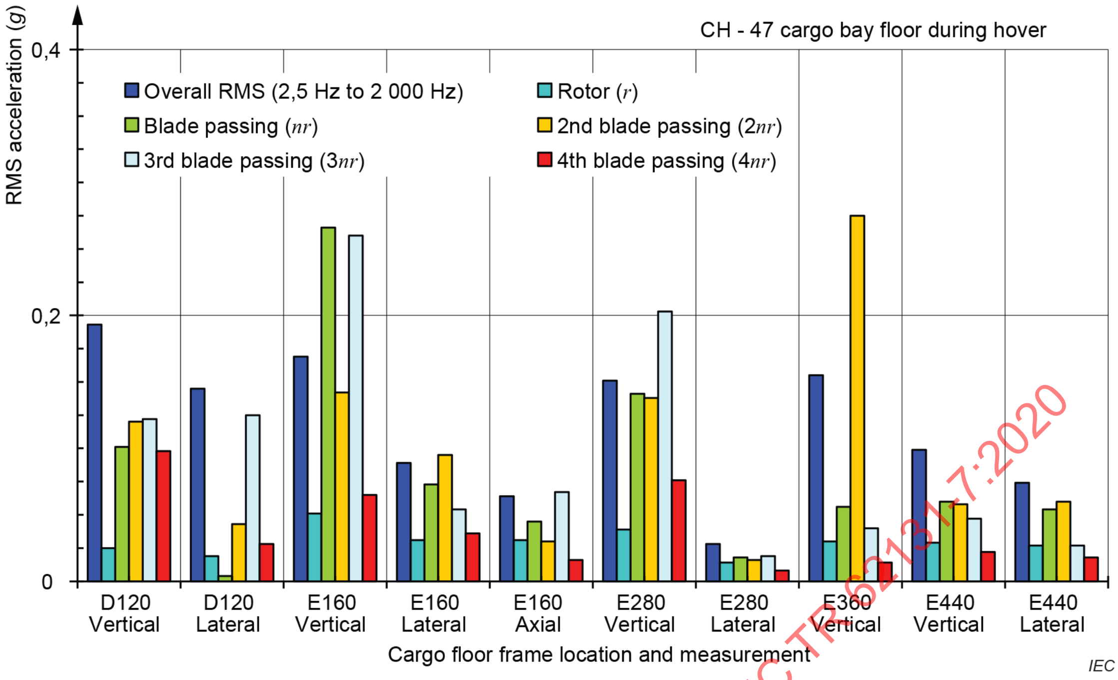

Figure 11 – Comparison of CH-47 vibration RMS severities across cargo bay floor during hover [1]

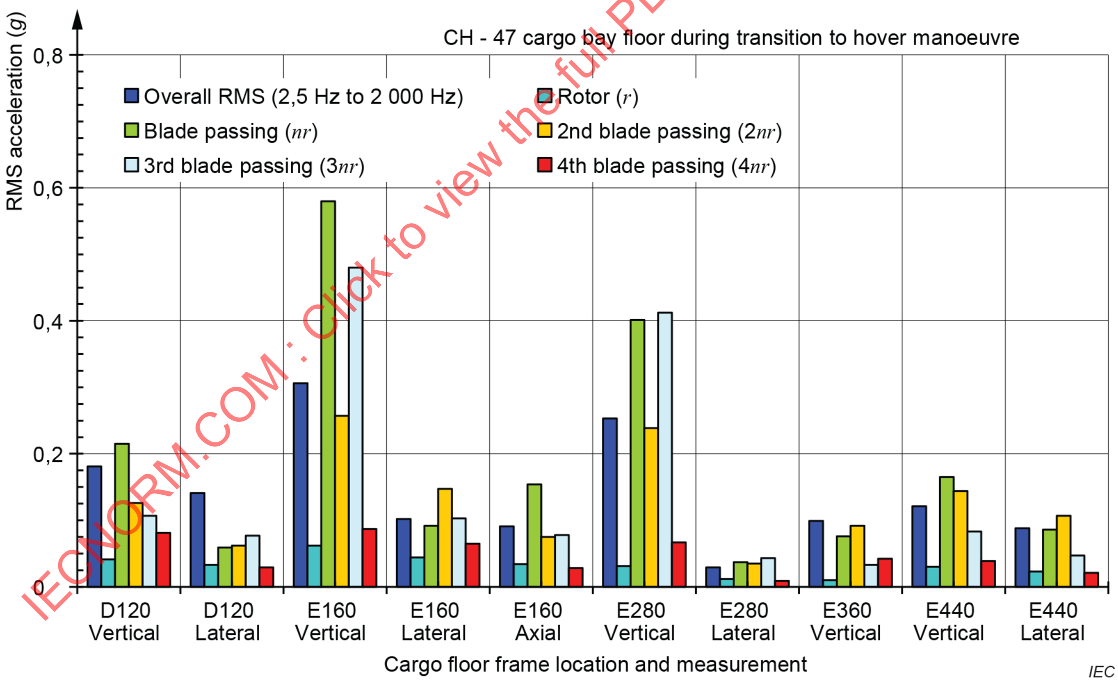

Figure 12 – Comparison of CH-47 vibration RMS severities across cargo bay floor during transition to hover manoeuvre [1]

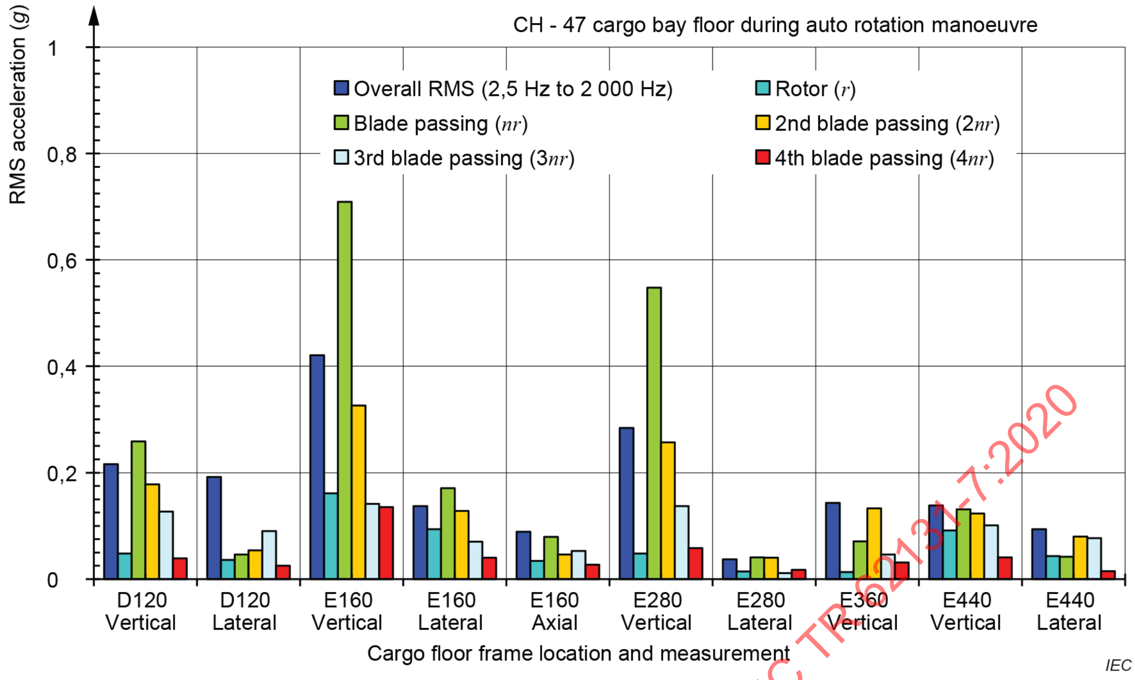

Figure 13 – Comparison of CH-47 vibration RMS severities across cargo bay floor during a transition to autorotation manoeuvre [1]

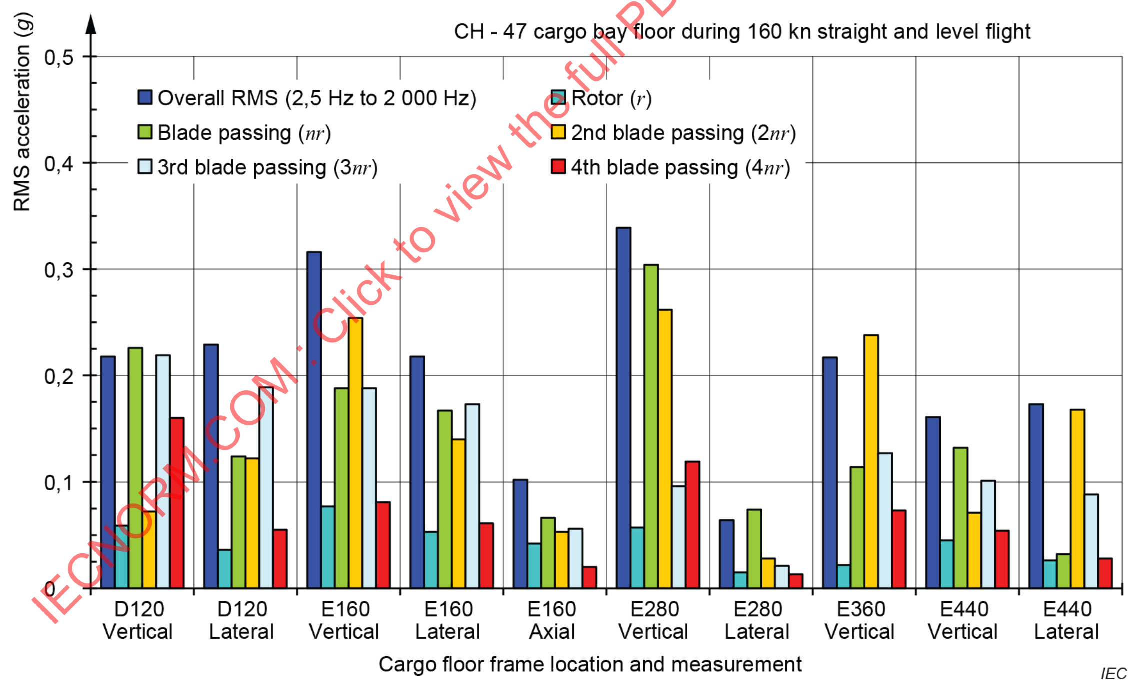

Figure 14 – Comparison of CH-47 vibration RMS severities across cargo bay floor during straight and level flight [1]

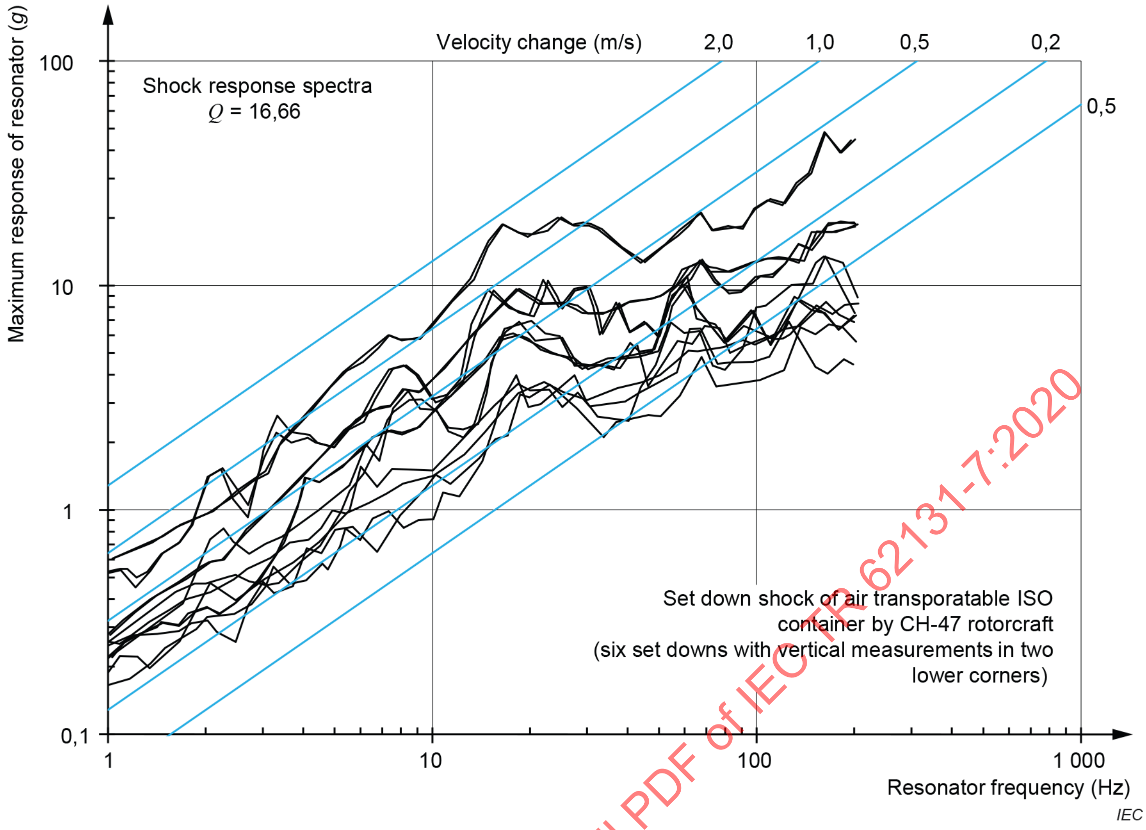

Figure 15 – CH-47 rotorcraft ISO container set down shock severities [2]

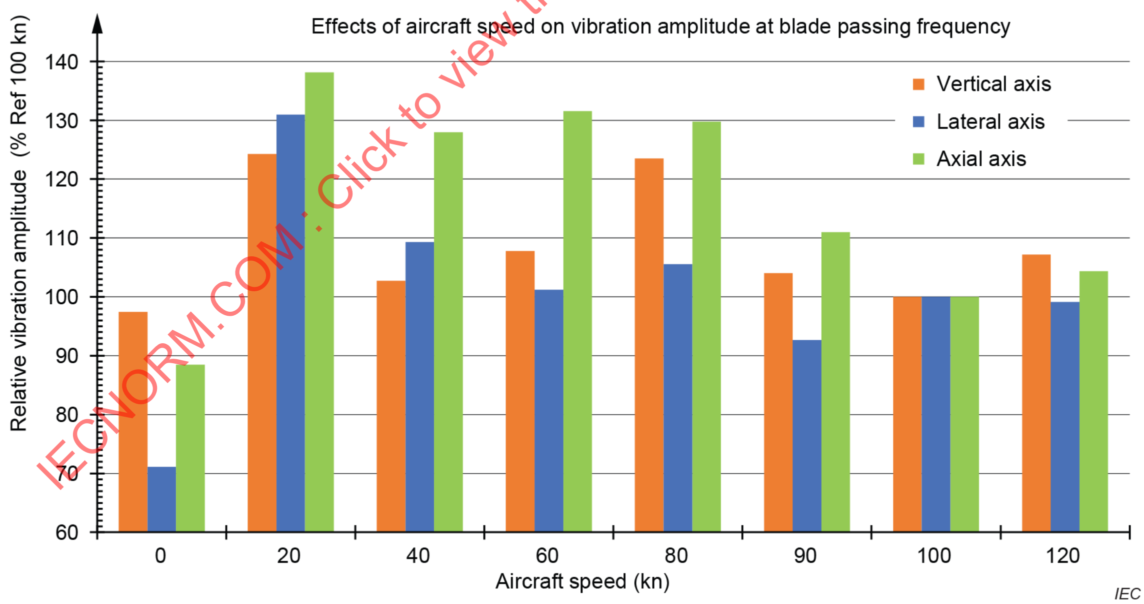

Figure 16 – Relative amplitude variations with airspeed for the Lynx rotorcraft [3]

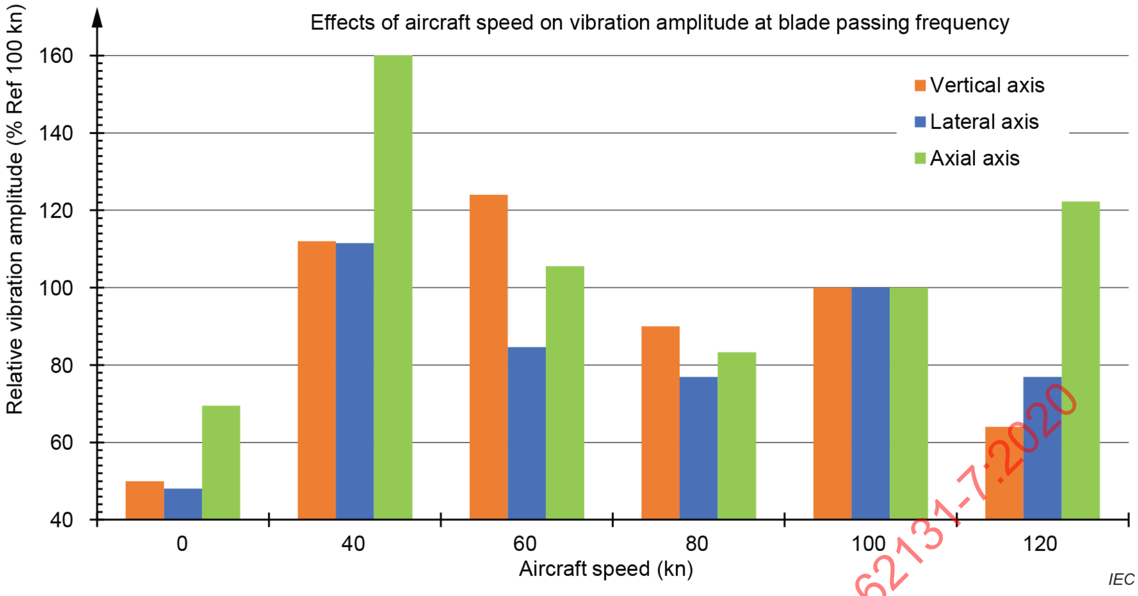

Figure 17 – Relative amplitude variations with airspeed for the Seaking rotorcraft [3]

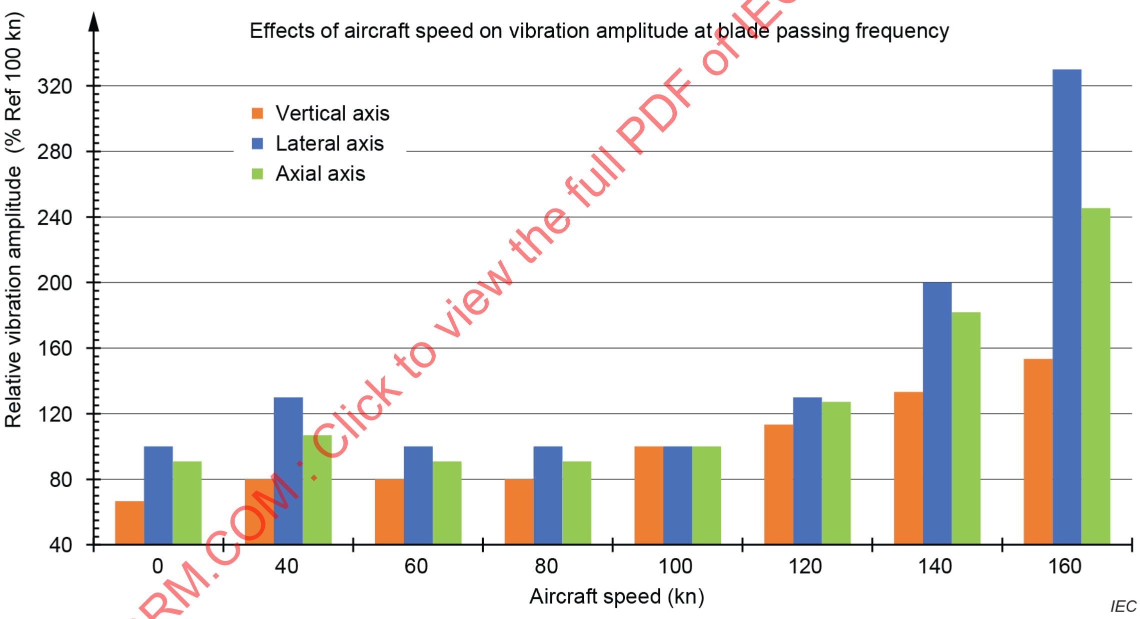

Figure 18 – Relative amplitude variations with airspeed for the Chinook rotorcraft [3]

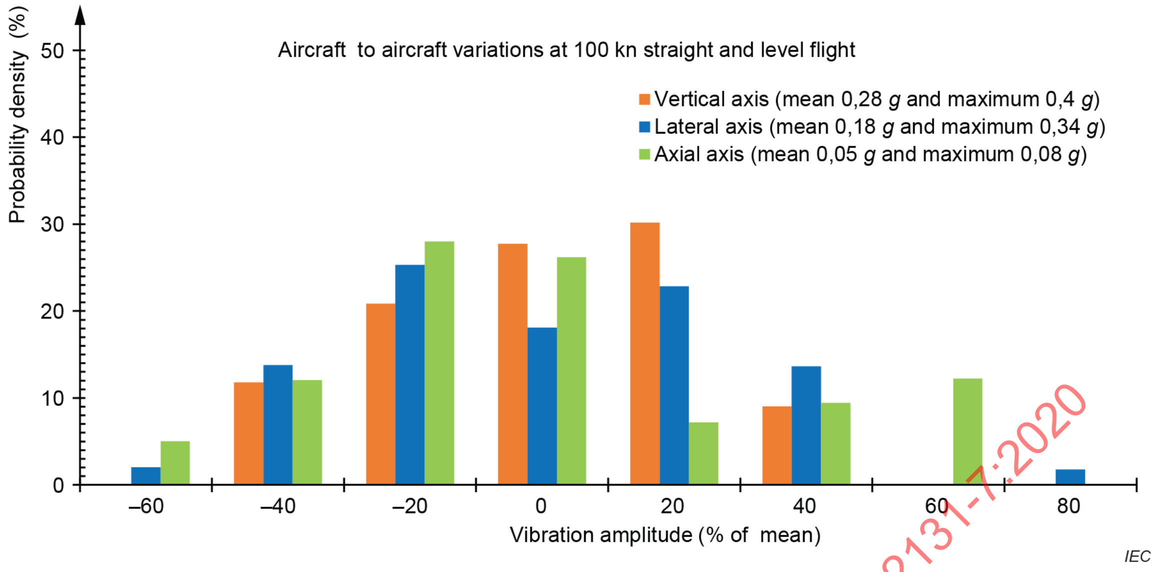

Figure 19 – Airframe to airframe relative amplitude variations for the Lynx rotorcraft [3]

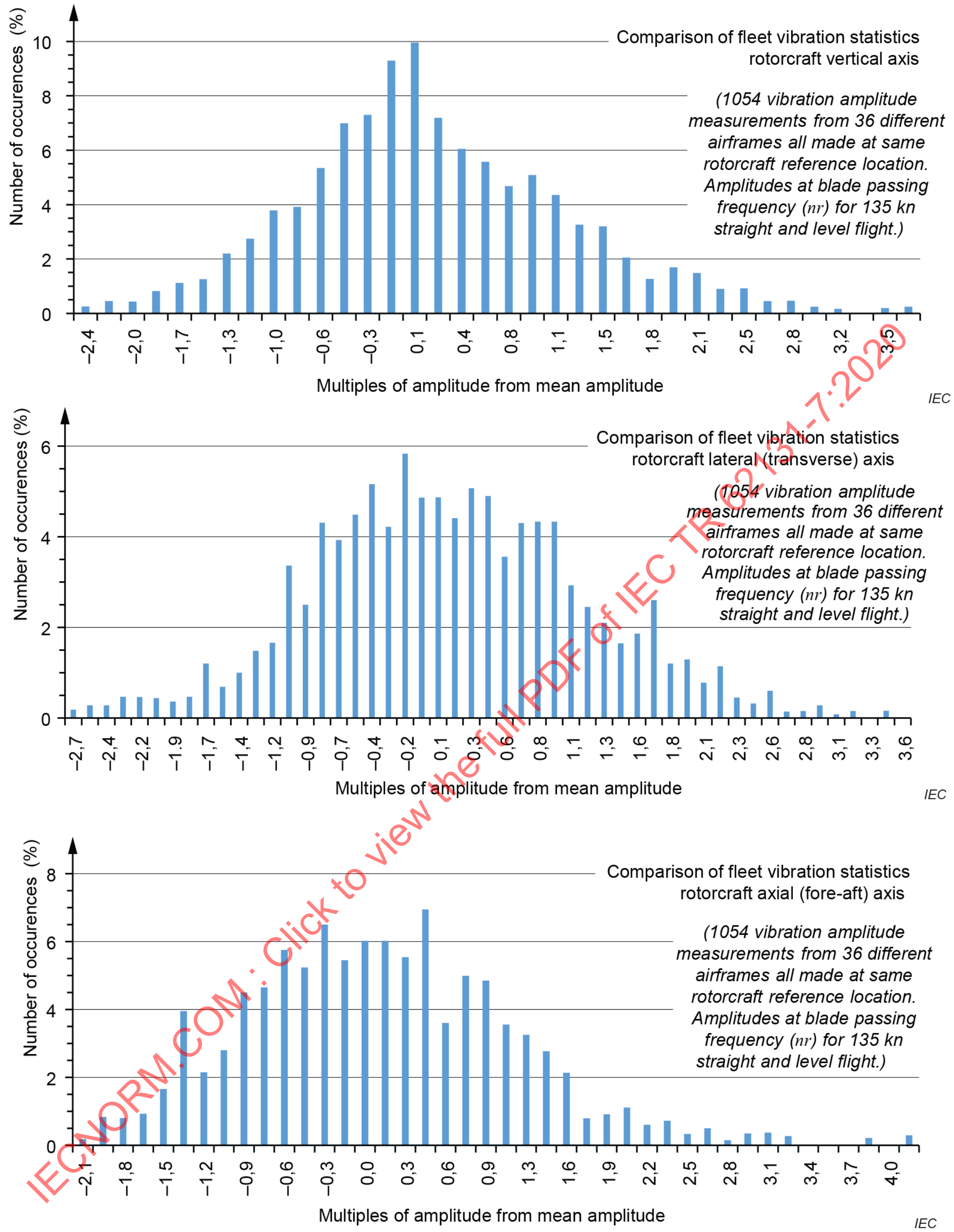

Figure 20 – Comparison of fleet vibration statistics [5]

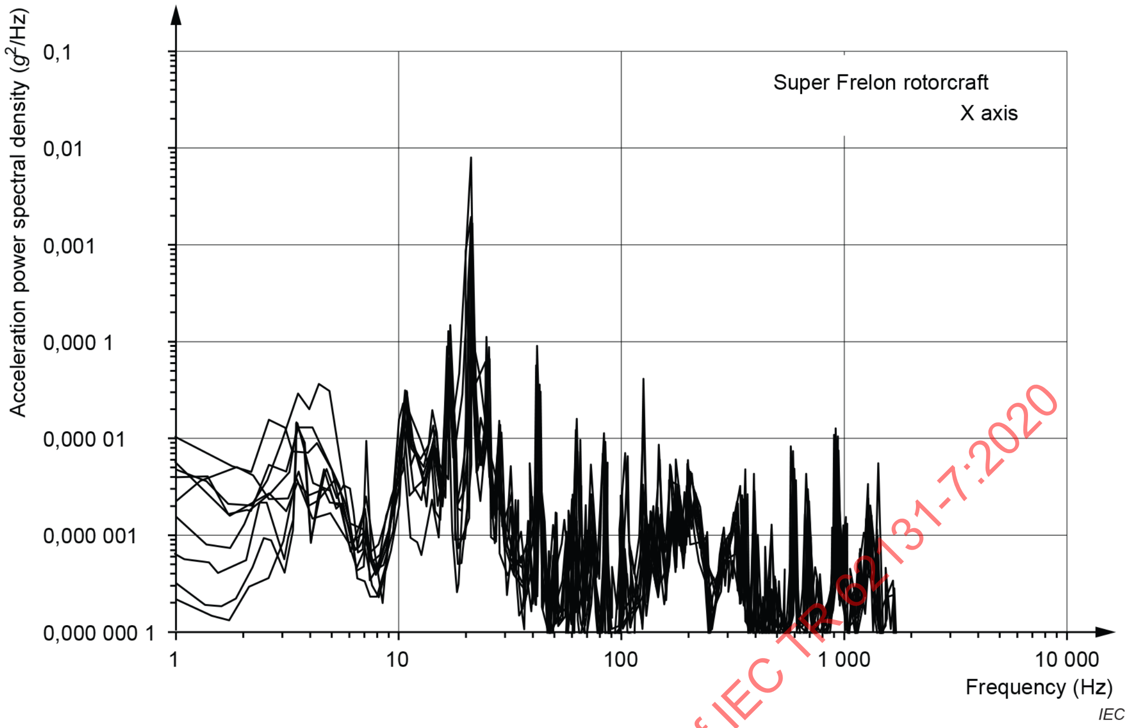

Figure 21 – Super Frelon rotorcraft measurements for X axis [6]

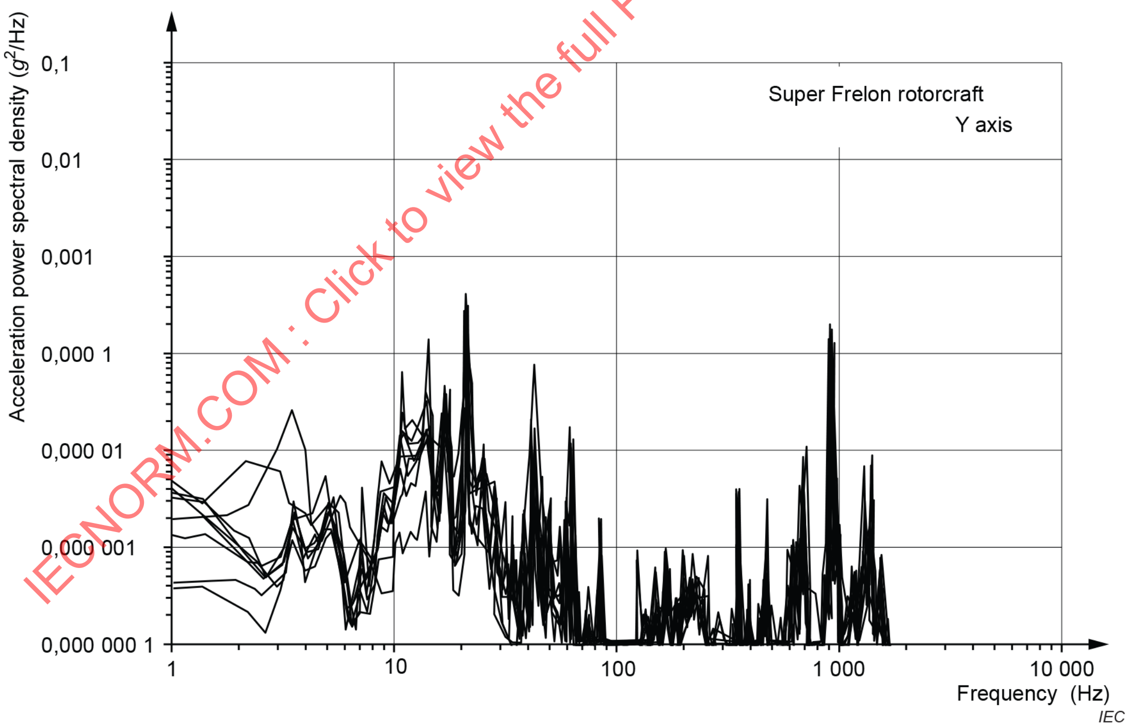

Figure 22 – Super Frelon rotorcraft measurements for Y axis [6]

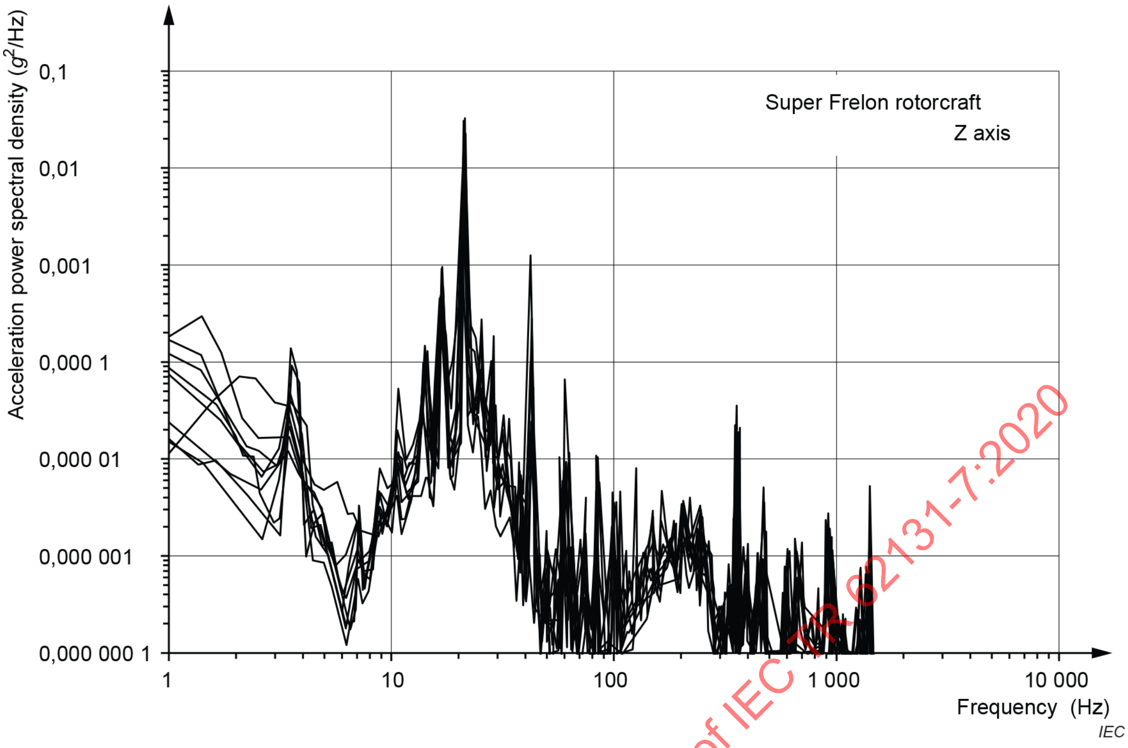

Figure 23 – Super Frelon rotorcraft measurements for Z axis [6]

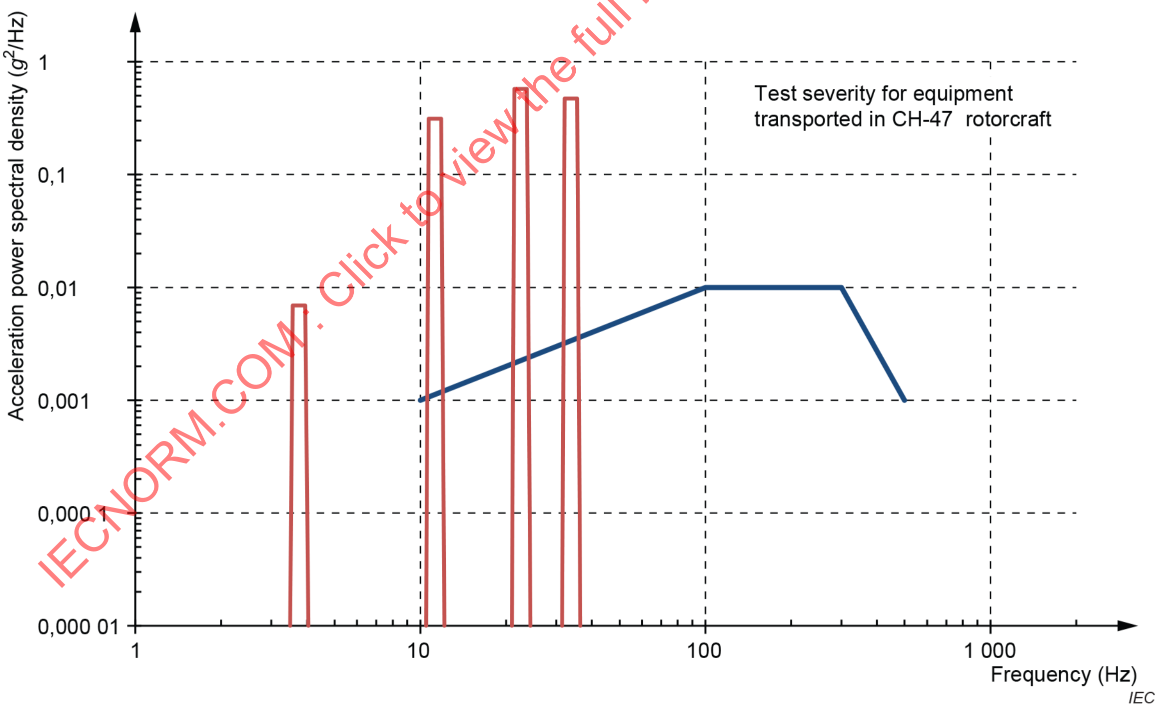

Figure 24 – Vibration test severity derived for the CH-47 rotorcraft using the approach of Mil Std 810 [9]

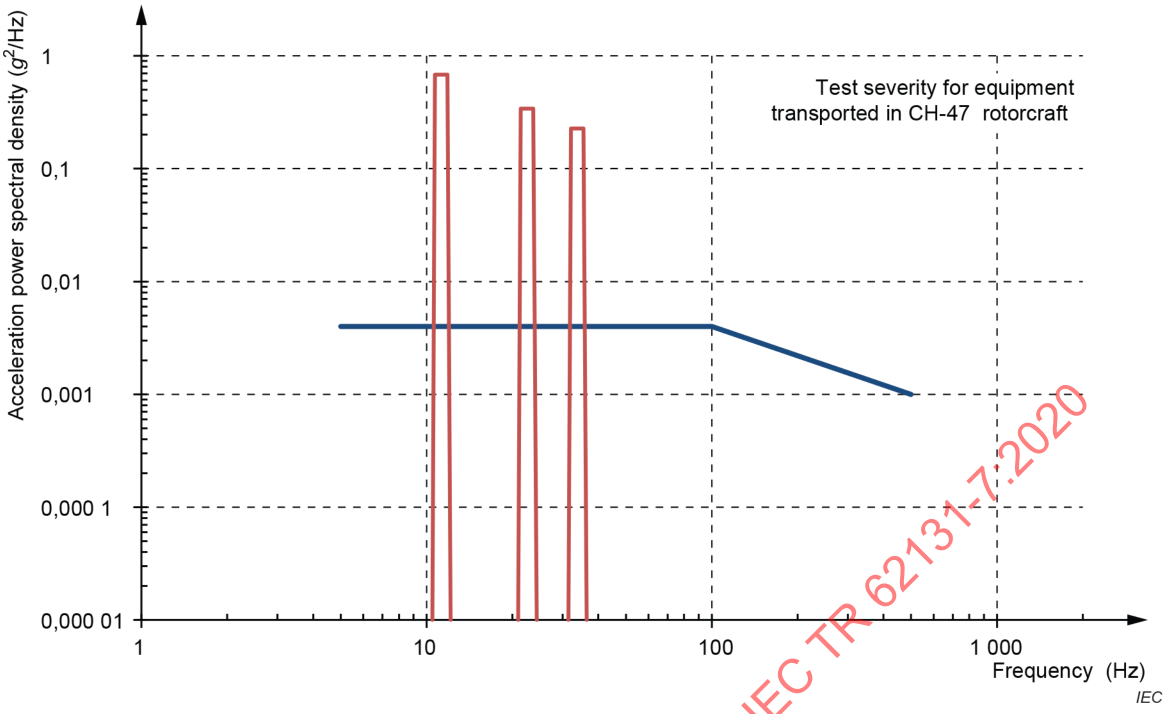

Figure 25 – Vibration test severity derived for the transportation of equipment in CH-47 rotorcraft using the approach of STANAG 4370 AECTP 400 Method 401 Annex D [10]

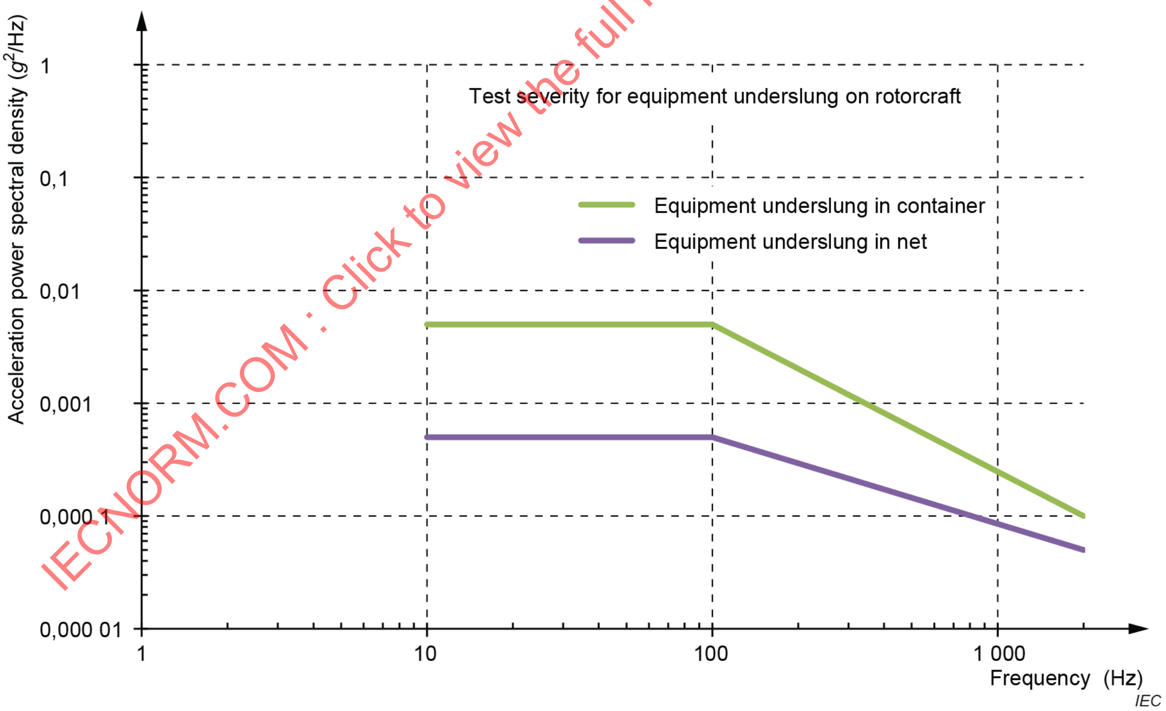

Figure 26 – Vibration test severity for equipment carried as underslung loads STANAG 4370 AECTP 400 Method 401 Annex D [10]

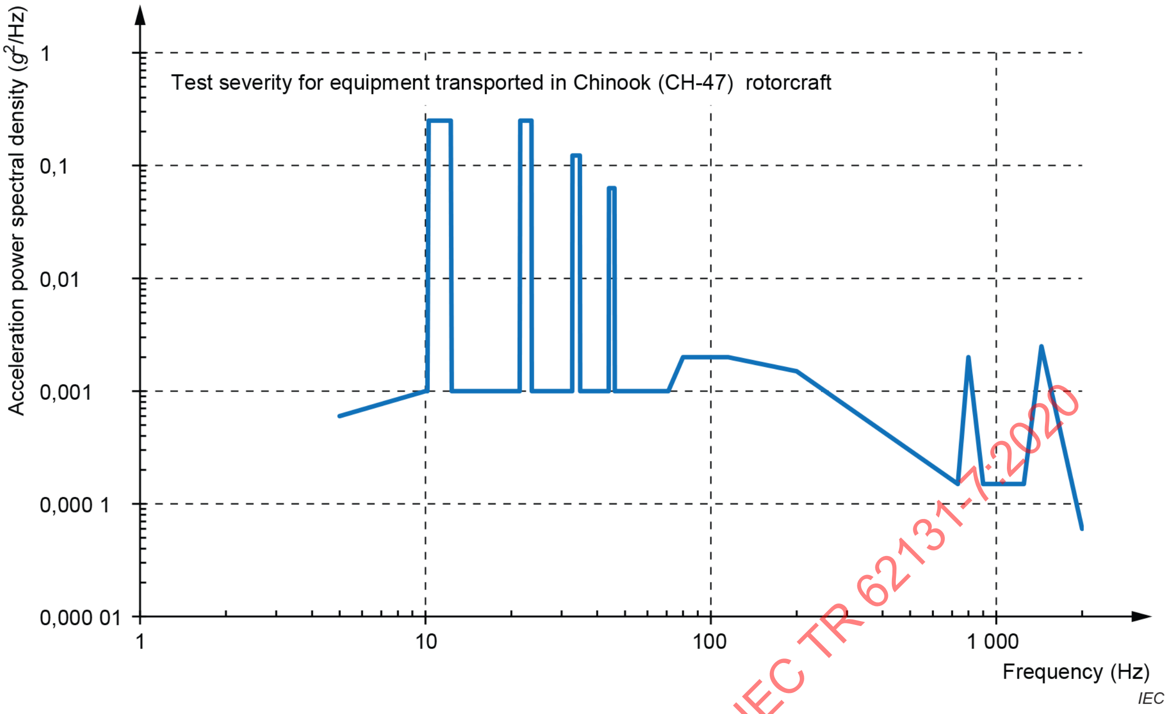

Figure 27 – Rotorcraft specific vibration test severities for Chinook (CH-47) from Def Stan 00-35 [5]

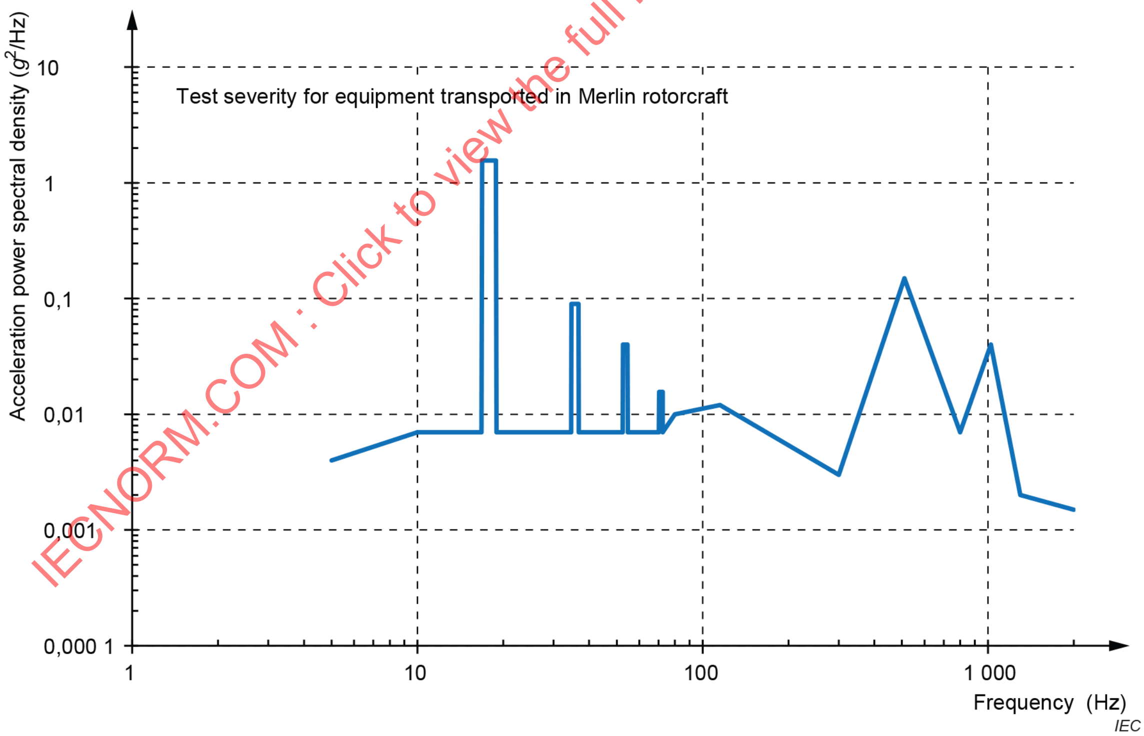

Figure 28 – Rotorcraft specific vibration test severities for Merlin from Def Stan 00-35 [5]

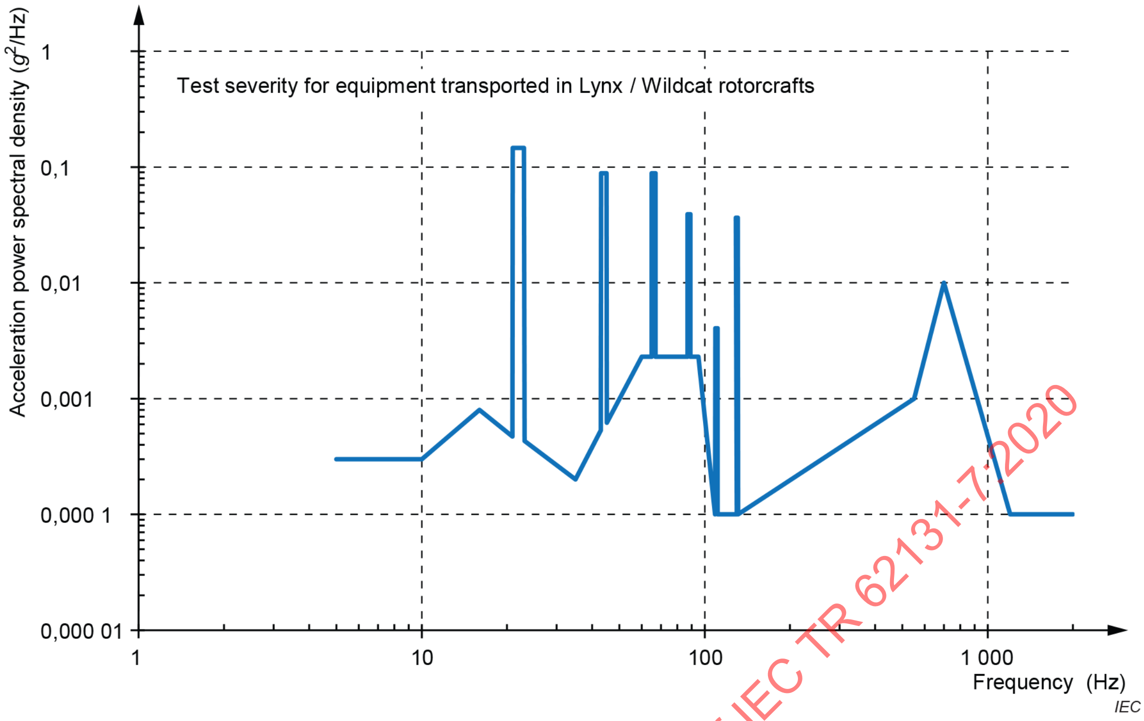

Figure 29 – Rotorcraft specific vibration test severities for Lynx/Wildcat from Def Stan 00-35 [5]

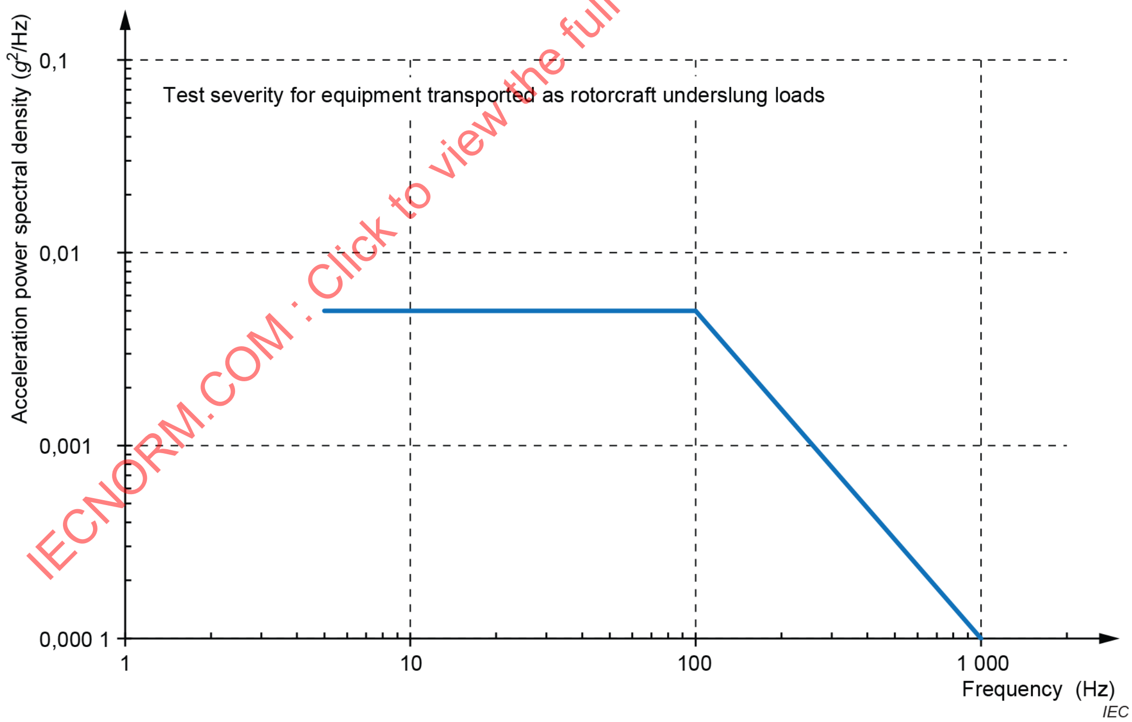

Figure 30 – Vibration test severities for underslung loads from Def Stan 00-35 [5]

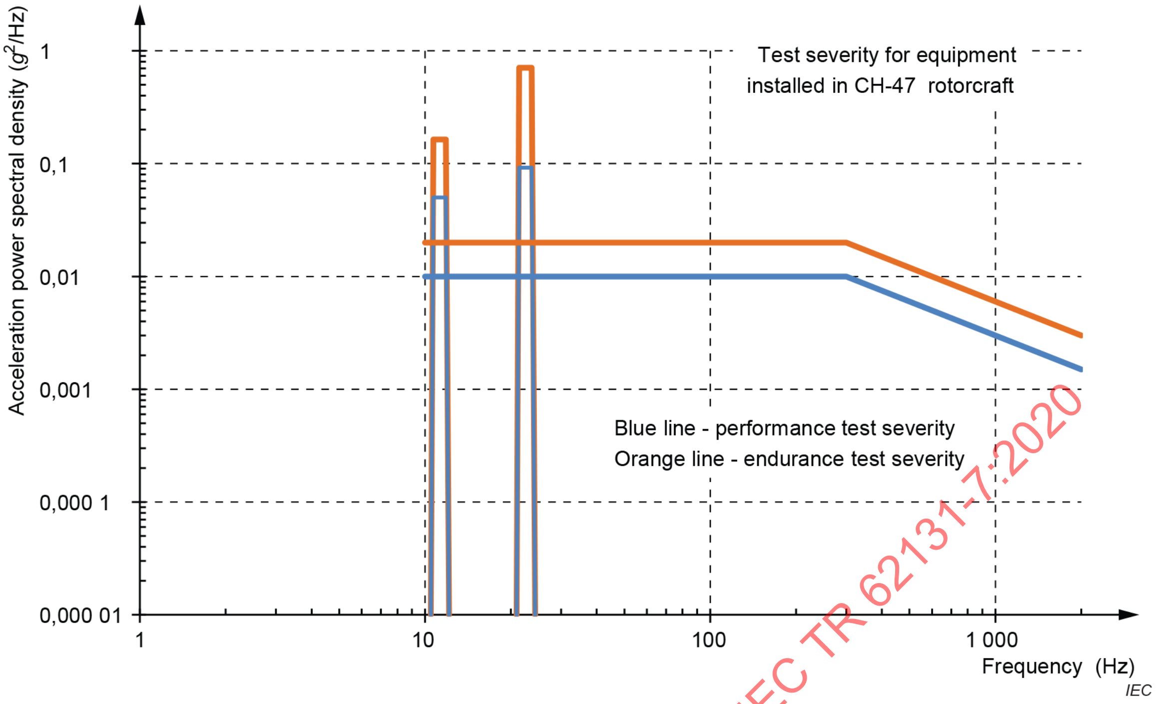

Figure 31 – Rotorcraft specific vibration test severities for CH-47 from RTCA/DO-160 [11] and EUROCAE/ED-14 [12]

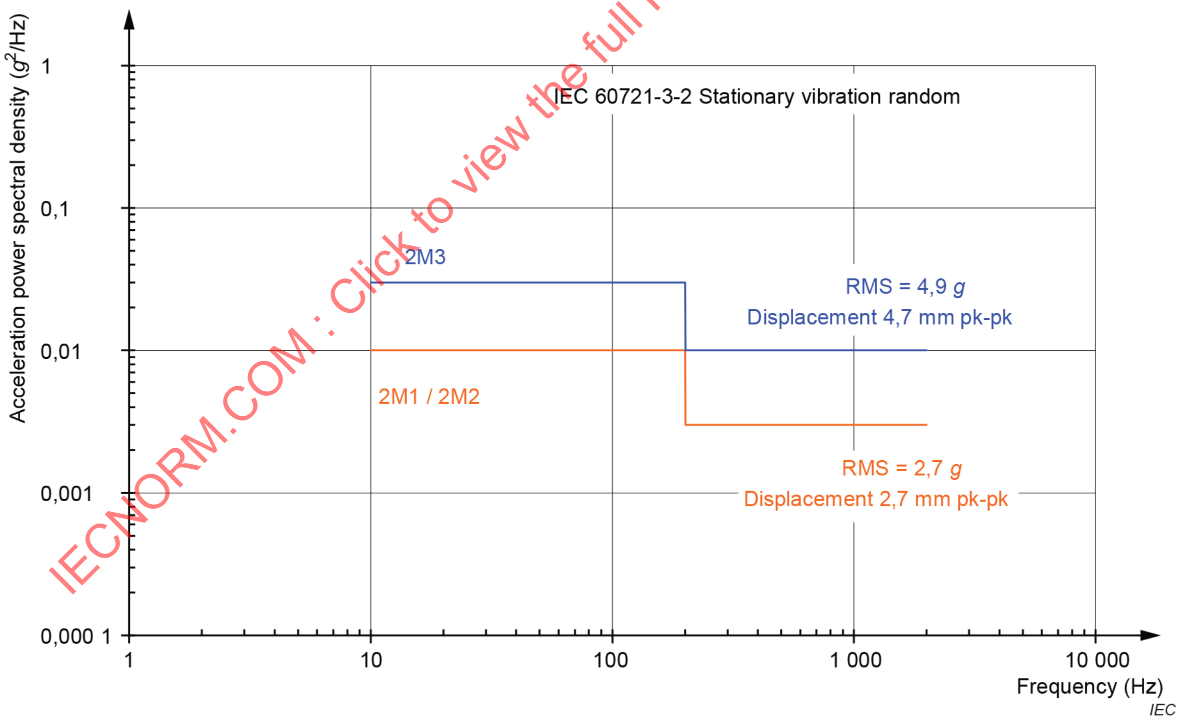

Figure 32 – IEC 60721-3-2:1997 [17] – Stationary vibration random severities

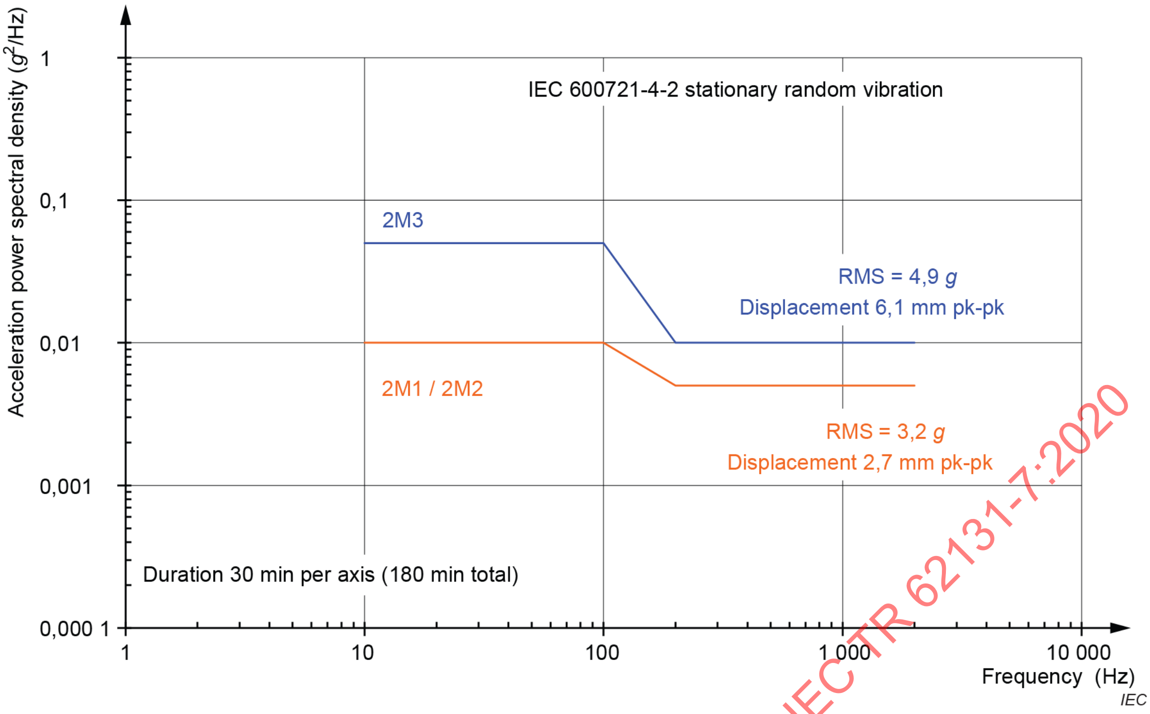

Figure 33 – IEC TR 60721-4-2:2001 [18]– Stationary vibration random severities

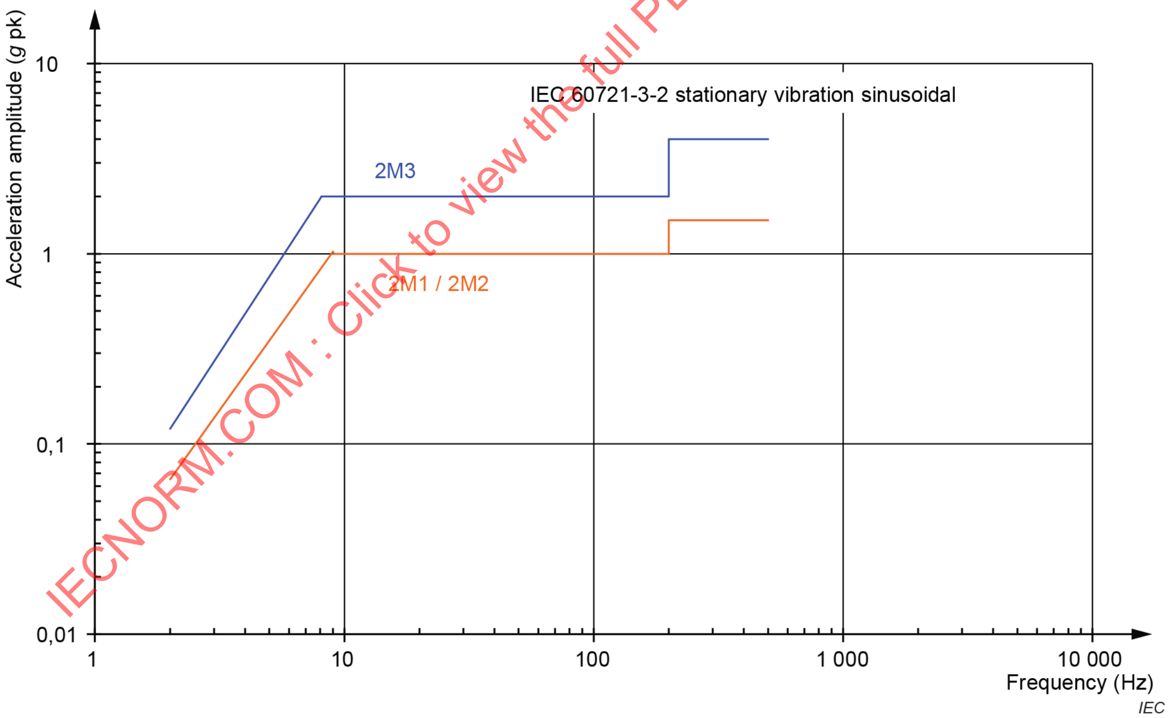

Figure 34 – IEC 60721-3-2:1997 [17] – Stationary vibration sinusoidal severities