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TECHNICAL REPORT

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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

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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- withdrawn,
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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

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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.