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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 6: Transportation by propeller aircraft

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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 6: Transportation by propeller aircraft

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FOREWORD

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IEC TR 62131-6, 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
104/687A/DTR	104/744/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- withdrawn,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
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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 6: Transportation by propeller aircraft

1 Scope

This part of IEC 62131 reviews the available dynamic data relating to the transportation of electrotechnical equipment. 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)[11][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[18].

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

[1] References in square brackets refer to the Bibliography.

4 Data source and quality

4.1 Vibration survey of four different propeller driven aircraft

Work was undertaken in 1989 to compare the source vibration on four different propeller driven aircraft (see [1]). This comparison work was undertaken to establish base data for a guidance chapter on propeller aircraft vibrations.

The four aircraft types encompassed by the vibration survey were: Britten-Norman Islander, BAe Jet Stream 100, BAe HS 748 and the Lockheed (Hercules) C130[2]. The data from the first three aircraft types were specifically collected for this comparison exercise during 1988. However, the data for the Lockheed C130 originates from several flights undertaken for another purpose during 1985. This Lockheed C130 data has commonality with other data referred to in this document. Information on each of the four aircraft is set out below:

– The Britten-Norman Islander is a lightweight twin engine aircraft fitted with reciprocating engines driving twin-bladed variable pitch propellers. With this arrangement different power settings can be achieved by varying both engine speed and propeller pitch. The general arrangement of the aircraft is shown in Figure 1.

– The BAe Jetstream 100 is a light utility transport aircraft fitted with twin, constant speed turbo-prop engines each driving a three bladed variable pitch propeller. With a fixed shaft rotational frequency of approximately 30 Hz, the blade passing frequency (shaft speed times the number of propeller blades) for this aircraft is fixed at approximately 90 Hz. The general arrangement of the aircraft is shown in Figure 2.

– The BAe HS 748 is a regional transport aircraft driven by twin turbo-prop engines fitted with four bladed variable pitch propellers. As the engines are variable speed, different power settings can be achieved by varying both engine speed and propeller pitch. For cruise conditions the propeller shaft rotational frequency is typically around 22 Hz, giving a blade passing frequency of around 88 Hz. The general arrangement of the aircraft is shown in Figure 3. This particular aircraft was fitted in a fire fighting configuration and this could be expected to give rise to increased vibration due to the presence of the large water tanks located externally under the fuselage.

– The Lockheed C130 Mk 1 aircraft, encompassed by this exercise, is a large transport aircraft driven by four fixed speed turbo-prop engines each powering a four bladed variable pitch propeller. The propeller shaft rotational speed is approximately 17 Hz producing a blade passing frequency of approximately 68 Hz. The general arrangement of the aircraft is shown in Figure 4.

The measurements on all four aircrafts used the same flight instrumentation. This 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 4 Hz to 2 500 Hz. The accelerometers were arranged in four tri-axial groups placed in the forward, centre and aft regions of the aircraft. The fourth transducer group was placed in the plane of the propeller disc. All the transducers were internally mounted on relatively stiff airframe locations.

Measurements were made for extended periods during the flight; the periods encompassed take-off, climb, cruise, descent, landing and taxi. The take-off phase included bringing the engines to full power, immediately before it started the take-off run. The landing phase included the use of reverse thrust, if that was appropriate. All the take-off and landings occurred on paved concrete runways of good length. That is no short take-off or landing conditions were considered.

2 Britten-Norman Islander, BAe Jet Stream 100, BAe HS 748 and Lockheed (Hercules) C130 are the trade names of products supplied by Britten-Norman, BAE Systems and Lockheed Martin respectively. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the products named.

The original analysis was mostly in the form of acceleration power spectral densities (PSDs), although very few of these are presented in the report. The report does not indicate the record duration used for the power spectral density analysis, but durations used by the agency, who made these measurements, are typically better than 30 s. The analysis frequency bandwidth was typically a little under 3 Hz. Whilst this is adequate to describe the broadband background vibration induced by propeller aircraft, it is inadequate to quantify, in terms of power spectral density amplitude, the tones arising from the propeller shaft, the blade passing frequency and the associated harmonics. The report indicates that peak hold spectra were used to estimate amplitudes at rotor and blade passing frequencies. However, the usual approach used by this measurement agency, in such circumstances, was to compute the tonal component root mean square (rms) by integration of the power spectral density amplitudes for each tonal component. The method used to quantify the vibration amplitudes at the propeller shaft, blade passing frequency and their harmonics, is a particular data analysis issue encountered when addressing propeller aircraft vibration data.

The report compares relative severities of the four aircraft in terms of overall rms for the different aircraft (Figure 5), flight conditions (Figure 6) and location within the aircraft (Figure 7). All these comparisons are in terms of relative amplitude i.e. they are all scaled such that the largest amplitude is to unity. The report also presents typical cruise power spectral densities for each aircraft type (Figure 8 to Figure 11).

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 Britten-Norman Islander aircraft flight measurements

Work was undertaken in 1988 to establish the vibration severities of a Britten-Norman Islander aircraft. The data from this measurement exercise was used within the comparison of the previous data set. This document contains analysis of the entire measured data.

The measurement locations are as set out in the review of the previous data set and shown in Figure 1 viz. tri-axial accelerometers on the floor of the cockpit, on the floor of the fuselage in the plane of the propeller, on the floor in the centre of the fuselage and on the floor at the aft fuselage. The flight conditions during which measurements were made comprised: take-off, climb, left turn, long left turn at cruise speed and at an altitude of 500 ft (152 m), straight and level at cruise speed at an altitude of 500 ft (152 m), descent and landing approach and landing.

The data is presented in the form of acceleration power spectral densities (PSDs) for each accelerometer at each of the seven flight conditions (84 plots in total). The report indicates the record duration used for each power spectral density analysis and analysis frequency bandwidth utilized, which are tabulated below (see Table 1).

Table 1 – Record durations and error estimates for measured data for Britten-Norman Islander aircraft flight measurements

Flight event	Analysis frequency bandwidth Hz	Measurement duration s	Random error %
Take-off	3,014	30	10
Climb	3,014	35	9,7
Left turn	3,014	60	7,4
Long left turn at cruise speed and 500 ft	3,014	75	6,6
Straight and level at cruise speed at 500 ft	3,014	175	4,3
Landing approach	3,014	30	10
Landing	3,014	15	15

The report does not separately quantify the tones arising from the propeller shaft, blade passing frequency or the associated harmonics tones. Although these are clearly identified in the analysis, the frequency they occur at is not fixed as the engine speed and propeller shaft speed varies.

The overall root mean square values (3 Hz to 2 000 Hz) for each accelerometer at each of the seven flight conditions are presented in Table 3. Selected power spectral densities are presented in Figure 12 to Figure 16. Inspection of the power spectral densities presented in the report indicates that the events have a spectral characteristic which would be expected from variable speed engine propeller aircraft. That is, the shaft and blade passing components occur at different centre frequencies for different flight conditions. With that said, the landing measurements indicate unusual characteristics, which do not appear to represent vibration conditions (they are more representative of shock conditions). For that reason the power spectral density for the landing event are not included here. The landing approach measurements are included as they mostly appear to be composed of vibration. However, the shape of the power spectral density is not entirely consistent with the other flight conditions.

The report only presents analysed data in the form of acceleration power spectral densities. The majority of these appear to have characteristics that would be expected from propeller aircraft. However, this is not the case for the information for the landing event. With this caveat the quality of the information is reasonable and meets the required validation criteria for data quality (single data item).

4.3 Lockheed C130 flight vibration measurements

This large transport aircraft is extensively used in military and civil transport applications and has been in-service for over four decades. The majority of the C130 aircraft fleet is used to transport cargo and can be considered to put utility above passenger comfort. As such the vibrations are generally at a level which would be unacceptable to the majority of civilian passengers. The vibration characteristics and severities from this aircraft are those used by a variety of international and national standards, to set the vibration test requirements for propeller aircraft equipment. As a consequence it is not surprising that, over the years, a variety of vibration measurement exercises have been undertaken on the aircraft. Although several measurement exercises on the C130 were considered for this work, the majority of the data presented are from measurement work undertaken by one agency. That work encompassed measurements undertaken over several decades on a number of different airframes and aircraft build standards. The measurement work reported was specifically undertaken to establish the source vibration on the fleet of the Lockheed C130 aircraft operated by the UK military forces (see [3]). This work was undertaken specifically to establish payload cabin floor vibration data for use in establishing test severities for the UK military standard relating to environmental testing requirements.

The various Lockheed C130 aircraft, encompassed by this exercise, were all UK military aircraft used for a variety of roles, including peace keeping and disaster relief operations. The general arrangement of the aircraft is shown in Figure 4. The vast majority of the worldwide fleet of C130 aircraft (and all the C130 aircraft encompassed by this document), utilize a four bladed straight propeller with a shaft rotational speed of approximately 17 Hz. This results in a characteristic blade passing frequency of 68 Hz. However, a recent variant of this aircraft replaced the four bladed straight propellers with six bladed propellers of a curved design. This results in a blade passing frequency of 102 Hz.

The various measurement exercises reported here for the C130, used essentially the same measurement locations and essentially the same flight instrumentation. The measurement instrumentation comprised 12 piezo-electric accelerometers and associated charge amplifiers which were recorded on an FM analogue recorder. The system provided an effective measurement frequency range of 4 Hz to 2 500 Hz. The accelerometers were arranged mostly in tri-axial groups placed in the cargo bay of the aircraft. In some cases axial (aircraft fore/aft) measurements were omitted. All the transducers were internally mounted on relatively stiff airframe locations, usually at aircraft frame locations.

In some of the flights reported here, additional measurements were made on two large containers with the transducers located on the pallet adjacent to the container/floor interface (i.e. as far as practicable measuring the vibration inputs to the containers). The two containers were over 2 000 kg in mass and approximately 1,5 m wide and 3,0 m long. They were positioned one behind the other in the aircraft cargo bay, together occupying the majority of the central zone of the aircraft. The two measurement locations were positioned at the aft port location of the aft container and the forward starboard location of the forward container. As such the measurements spanned the total length of the two containers. For these more recent measurements the FM analogue recorder was replaced with a digital recorder.

Measurements were made for statistically reasonable periods, generally in excess of 30 s, during the flight and encompassed take-off, climb, cruise, descent, landing and taxi. The take-off phase included the period necessary to bring the engines to full power immediately before the start of the take-off run. The landing phase included the use of reverse thrust. All the take-off and landings measured were on adequate length good quality concrete paved runways.

The analysis was mostly in the form of acceleration power spectral densities (PSDs), although a certain amount of peak hold analysis was also undertaken. The data reports include a statement of the measurement record duration and bandwidth for the power spectral density analysis. As such, random error can be established for each analysis and the appropriate values are shown in Table 2.

Table 2 – Record durations and error estimates for measured data for Lockheed C130 flight vibration measurements

Flight 3 event	Duration s	Random error %	Flight 4 event	Duration s	Random error %
Pre-flight taxi	30	11	Full power run	10	18
Take-off	30	11	Take-off	20	13
Climb	60	8	Climb	80	7
Cruise and turns	40	9	Cruise	60	8
Descent	40	9	Descent	160	5
Landing approach	40	9	Landing approach	60	8
Landing	30	11	Landing	20	13

The analysis frequency bandwidth was typically a little under 3 Hz. This is adequate to describe the broadband background vibration induced by propeller aircraft. However, this analysis bandwidth is not really adequate to quantify the tones arising from the propeller shaft, blade passing frequency and the associated harmonics. In this case peak hold spectra were used to give a more reliable estimate of the amplitudes at the blade passing tones during transitory conditions. Specifically, the amplitudes of the tonal peaks were quantified from the peak hold values by assuming they represent sinusoidal tones in the analysis bandwidth. Provided the tones remain stationary in a single analysis band, the derived tonal values accurately represent the largest value occurring over the duration of the record, averaged over blocks of approximately 0,4 s duration.

Figure 17 to Figure 20 compare the tonal peak amplitudes for the vibration components at engine shaft frequency, first propeller blade passing frequency and the subsequent two harmonics of blade passing frequency. These comparisons are made for three locations (forward, middle and aft) of the cargo bay and are presented separately for take-off, climb, cruise and landing (specifically the use of reverse thrust). Figure 21 shows the peak tonal value for the blade passing frequency for a range of flight conditions for which measurements are available. Figure 22 shows similar information but for the overall vibration root mean square acquired between 3 Hz and 2 000 Hz. Figure 23 to Figure 32 present selected acceleration power spectral densities for different locations and flight conditions from two flights (designated here flights 3 and 4). These two flights used different, but overlapping, measurement locations. Table 4 and Table 5 show the actual overall vibration root mean square values from these two flights for all measurement locations and flight conditions for which data are available.

The information in this document has some limitations but it does encompass the main cargo hold of the Lockheed C130 aircraft. The quality of the information is reasonable and meets the required validation criteria for data quality (single data item).

4.4 Lockheed C130 landing shock measurements

Work undertaken in 1988 reviewed landing shock measurements from four flights of a Lockheed C130 aircraft (see [4]). This work was primarily undertaken to establish cabin floor shock severities for the UK military standard relating to environmental testing requirements. The measurement exercise included both normal and short landings. The latter were included because this propeller aircraft is able to use short and temporary runways at remote locations. The landing shocks arising from such use is typically more severe than would be the case for normal landings. Indeed this measurement exercise arose partly because a payload carried by a C130 aircraft (and some of the aircraft equipment) had been damaged as a result of a short landing on a temporary runway during disaster relief activities.

The Lockheed C130 Mk 1 aircraft, encompassed by this exercise, is that utilized and described in 4.3. The measurements used flight instrumentation comprising six piezo-electric accelerometers and associated charge amplifiers which were recorded on a 14 channel FM recorder. The system provided an effective measurement frequency range of 2 Hz to 250 Hz with a subsequent acquisition rate of 1 000 sample per second (sps). The accelerometers were arranged in two tri-axial groups; one placed at aft port location of one container, the other at forward starboard location of a second container (see 4.3 for specific information on the containers). Measurements were made throughout the landing phase with the touch down event specifically 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 (Q) of 16,66 to facilitate comparison with some historic US data.

The report contains time history and the shock response spectra from four flights, five landings and from the six measurement channels. Within these data, the third flight contained one tactical landing and one normal landing. The remaining flights were all normal landings. Figure 33 to Figure 35 show the shock response spectra from all four flights for the aircraft vertical, lateral and longitudinal axes.

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).

4.5 Supplementary data

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

The SRETS study (see [5]) was undertaken during 1998 and reviewed both measured data sources and test severities for a variety of methods of transportation. It compared two measured data sets related to propeller aircraft. One of those data sets is from the UK defence standard DEF STAN 00-35 [6], but that data set is already included in this document. The second data set was from the French military standard GAM-EG-13 [7]. That standard includes information from the Transall C-160[3] aircraft. The Transall C-160 is a heavy transport aircraft (approximately 50 000 kg) powered by two turboprop engines each driving a four-bladed propeller. The measured information included in GAM-EG-13 relates to two ground and seven flight conditions. The measurements are from only one fuselage floor location and the specific location is not stated. The measured information is presented in the form of acceleration power spectral densities for take-off, cruise and landing, which are included here as Figure 36, Figure 37 and Figure 38 respectively. Overall root mean square vibration severities are also presented, listed here in Table 6, and are assumed to be over the frequency range 1 Hz to 1 500 Hz. These overall root mean square values are lower than for the other aircraft included in this document, but not unreasonably so. The power spectral densities indicate that the blade passing tone is dominant and the frequency of the tone appears to vary between 45 Hz to 55 Hz.

As part of an exercise, in the early 1970’s, to authenticate test severities for the US military specification MIL STD 810[23], J.T. Foley [8] at the US Sandia National Laboratories undertook an extensive exercise to establish transportation severities on a number of platforms including two propeller aircraft i.e. the Lockheed C130 and the (now obsolete) Douglas C133. Unfortunately, the analysis process used by Foley throughout his work is relatively unique and not directly comparable with the information presented in this document. Nevertheless, the information generated by Foley seems to be largely consistent with that already reviewed in this document.

As already indicated a number of test standards adopt a shaped random profile, which seem to be mostly based upon the vibration characteristics of the Lockheed C130. One standard that differs from that approach, and could be considered to be the closest to the IEC 60721 (all parts) severities, is that of the US standard RTCA/DO-160 [9], which is identically worded to the European standard EUROCAE/ED-14 [10]. Those standards adopt a sine vibration envelope for equipment installed in aircraft with reciprocating or turbo-propeller engines. The severities for equipment at fuselage locations are 3 *g* peak at frequencies between 55 Hz and 150 Hz. However, the 155 Hz value is the upper limit of that particular test (although others do go up to 500 Hz).

A certain amount of supplementary data was reviewed for this document, which unfortunately could not be made publicly available in time for publication. One such set of data is that from a latter variant of the traditional Lockheed C130. That variant uses the same propeller shaft rotational speed as earlier aircraft, but with a six bladed propeller of curved design. As a consequence the fundamental blade passing frequency now occurs at approximately 102 Hz. Measured information in the form of an acceleration power spectral density for cruise flight is included here as Figure 39. The modified shape of the propeller has reduced the vibration amplitude of the fundamental blade passing tone but has resulted in increased vibration responses at the harmonics of the blade passing frequency.

Another supplementary data set reviewed for this document, which unfortunately could not be made publicly available in time for publication, was from an Airbus A400M[4]. Whilst this is a predominantly military aircraft, it does represent a high performance propeller aircraft design which has different characteristics to the other aircraft considered here. The Airbus A400M is a large propeller transport aircraft, which adopts a different propulsion management approach to that of the preceding aircraft types. The aircraft uses four turbo-prop engines, which operate at a range of engine speeds. These engines are coupled to eight bladed variable pitch propellers of curved design, two of which rotate clockwise and two anticlockwise. As both the engine speed and propeller blade pitch are variable and controllable, a range of blade passing frequencies can occur during flight. This is illustrated in Figure 40 which comprises acceleration power spectral densities for a number of different cruise flight conditions. The curved shape of the blade reduces the intensity of the vibrations arising at

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3 Transall C160 is the trade name of a product supplied by Transporter Allianz. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named.

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