PD IEC/TR 62131-6:2017

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Environmental conditions - Vibration and shock of electrotechnical equipment

Part 6: Transportation by propeller aircraft

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National foreword

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TECHNICAL REPORT

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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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IEC TR 62131-6, which is a Technical Report, has been prepared by IEC technical committee 104: Environmental conditions, classification and methods of test.

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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

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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.

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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.

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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.

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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

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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.

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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

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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

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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

[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.

[4] Airbus A400M is the trade name of a product supplied by Airbus Defence and Space. 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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fundamental propeller blade passing frequency, but increases the severity of the subsequent harmonics. Additionally, the high propeller blade tip speed can, in some flight conditions, give rise to supersonic aerodynamic effects which can further increase the severity of the subsequent harmonics. As a consequence, under certain operating conditions, the aircraft can generate significant vibration severities in the mid to higher frequency ranges, as well as introducing extensive tonal responses. As a consequence, the cruise vibration severities can be particularly high, compared to other propeller aircraft.

5 Intra data source comparison

5.1 General

The purpose of the discussion addressed in the following subclauses is to review each data source for self consistency.

5.2 Vibration survey of four propeller driven aircraft

The purpose of the vibration survey of four propeller driven aircraft (see [1]) was to supply comparison information for a UK military standard. As such the work was largely undertaken to facilitate an inter data source comparison. Whilst the report does not include any discussion on the different responses between different types of aircraft, such a discussion occurred when the information was considered for inclusion in the UK military standard.

At the time that this measurement work was undertaken, a number of national and international standards represented the vibration severities for transportation in propeller aircraft with a test spectrum typical of that seen for the traditional Lockheed C130. That is, a relatively low background random vibration severity onto which are superimposed tones at the blade passing frequency as well as the next three harmonics. The tone occurring at the fundamental blade passing frequency is represented as the most severe with the amplitudes of the subsequent harmonics falling in amplitude by typically 6 dB from that of the preceding tone order. The propeller shaft speed component is typically considered negligible and ignored.

The survey of four propeller driven aircraft confirmed that the common representation of propeller aircraft vibration test severities was indeed applicable to the Lockheed C130 especially during cruise flight conditions. However, the work also indicated that such a severity was not entirely applicable to other aircraft and flight conditions. It was the case that all four of the propeller aircraft surveyed indicated a relatively low background random vibration level. The survey also showed that onto this broadband random vibration level was superimposed a number of tones. Although the amplitude of the fundamental blade passing tone was usually dominant, it was not necessarily always the case. Moreover, the work indicated that the amplitude of the harmonics of the fundamental blade passing tone did not necessarily fall in amplitude in such a clear fashion as indicated for the Lockheed C130 during cruise. Additionally, the work indicated that for some aircraft the fundamental blade passing tone did not necessarily occur at a fixed frequency. Rather for those aircraft types it varied over a range of frequencies depending upon flight condition.

As a common representation of propeller aircraft vibrations is based upon the Lockheed C130 aircraft, it is useful to consider that aircraft first. Inspection of Figure 5 would suggest that, of the four aircraft considered, the Lockheed C130 produces the most severe vibration conditions, but only during take-off and landing. During cruise flight conditions of the Lockheed C130, the vibration severities induced are not that different from the other aircraft considered.

The Britten-Norman Islander aircraft is physically significantly different from the Lockheed C130, in that it is a lightweight twin engine aircraft fitted with reciprocating engines driving twin-bladed variable pitch propellers. With this arrangement the shaft and blade passing tones will vary in frequency for different power settings and consequently during different flight conditions. These characteristics are common for most lightweight propeller aircraft fitted with

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reciprocating engines. For the Britten-Norman Islander aircraft, the fundamental propeller blade passing frequency varies between 75 Hz and 90 Hz for different flight conditions, with cruise occurring at the lower end of this range. The greatest vibration severities occur at take-off when a considerable number of harmonics, of the fundamental propeller blade passing frequency, occur. During cruise, the second and third blade passing harmonic are also predominant on the vibration spectra. Clearly these conditions are not represented by fixed frequency tones, used for test severities based upon the Lockheed C130.

The BAe HS 748 is a regional passenger and cargo 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. Although the engine shaft speed and blade passing frequency vary, the range of variation is less than that found with a reciprocating engine. However, for some equipment the variations in blade passing frequency, particularly during take-off and landing, may be sufficient to negate any assumption that the blade passing frequency remains fixed during all flight conditions. These characteristics are typical of a range of medium sized aircraft with turbo-prop engines. The cruise shaft speed for the BAe HS 748 is reasonably constant at 22 Hz giving a blade passing frequency of 88 Hz. In this case, the vibration amplitude of the propeller induced vibration tones at the second, third and fourth harmonics of the blade passing frequency are as severe as that at the blade passing frequency itself.

The BAe Jetstream 100 is a light utility transport aircraft fitted with twin, constant speed turbo-prop engines. As a consequence, the shaft rotational frequency (30 Hz) and blade passing frequency (90 Hz) are essentially fixed for all flight conditions, in a similar manner to that of the Lockheed C130. In this case, the vibration amplitude of the propeller induced vibration tones at the fourth, fifth and sixth harmonics of blade passing are almost as severe as that at the fundamental blade passing frequency. In the plane of the propeller, the vibrations occurring at shaft frequency for this aircraft are particularly predominant.

The extent of the vibration information, presented in the report on the vibration survey of four propeller driven aircraft, is relatively limited, especially with regard to the amplitude of the blade passing tones. The report indicates that peak hold spectra were used to estimate the amplitudes of the tones but does not present actual values. 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 Britten-Norman Islander aircraft flight measurements

As already observed, the vibration responses generated by the Britten-Norman Islander aircraft are significantly different from those of the Lockheed C130. The information contained in the specific report on the measured vibration severities from the Britten-Norman Islander aircraft, expands on these differences.

The overall vibration severities, shown here in Table 3, indicate that take-off generates the most severe vibration severities within the aircraft cargo bay and particularly at fuselage locations in the plane of the propellers. Typically the overall vibrations are four to five times greater at take-off than during cruise. Not only do the greatest vibration severities occur at take-off, but the resulting acceleration power spectral density (Figure 13 and Figure 14) contain a number of harmonic tones of significant amplitude. The acceleration power spectral densities, presented in Figure 12 to Figure 16, indicate that the predominant tone is that at the fundamental blade passing frequency which varies between 75 Hz and 90 Hz. The upper frequencies arise during take-off conditions and the lower frequencies during cruise and descent.

The extent of the vibration information, presented in the report on the vibration of the Britten-Norman Islander aircraft, is relatively limited, especially with regard to the amplitude of the blade passing tones. Nevertheless, the data appear 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.

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5.4 Lockheed C130 flight vibration measurements

The reports on the vibration severities of the Lockheed C130 aircraft encompass two flights which encompass the majority of the payload area. From the information presented in the reports, the amplitude of the primary tonal components can be quantified separately (Figure 17 to Figure 21) to the power spectral density plots. The report used a variant of the peak hold spectra to estimate amplitudes at the blade passing frequency and its harmonics. These were converted into “equivalent peak” values by assuming the tones are sinusoidal and exist only in a single frequency band. This is a pragmatic approach, useful when the vibrations are non-stationary such as during take-off, and appears to compare reasonably well with other methods. The reports additionally present the overall vibration severity (specifically the root mean square of the vibrations between 3 Hz and 2 000 Hz).

The most severe conditions occur during take-off (including the pre take-off full power run) and are shown here in Figure 21 and Figure 22. The next most severe vibration condition arises during reverse thrust on landing. Typically, during aircraft cruise the vibration severities are around half the take-off values. The most severe vibrations occur in the plane of the propeller, with the severities progressively falling for aircraft locations both forward and aft of that plane. Although not reproduced here, the vibration transmission into the two large containers have the characteristics of a simple mechanical one degree of freedom isolation system. This is not entirely surprising as the containers are relatively heavy items tied down to a relatively flexible aircraft payload floor (so together acting as a predominantly one degree of freedom vibration isolator). In this case the natural frequency of the one degree of freedom system is around 20 Hz. At that frequency, the containers are likely to experience slightly amplified vibrations from the shaft speed tonal component, but the higher frequency propeller blade passing vibration components would be attenuated.

As already noted, the Lockheed C130 turbine engines operate at a fixed speed in conjunction with variable pitch propellers. As a consequence, shaft, blade passing and their harmonics, each occurs at a constant frequency regardless of flight condition. This is clearly apparent in Figure 23 to Figure 32. The dominant tonal component is almost always at blade passing frequency.

Overall, the data appear 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.

5.5 Lockheed C130 landing shock measurements

The Lockheed C130 landing shock measurements 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 landing gear of this type of aircraft. The dominant response frequency in the vertical axis is around 15 Hz and between 15 Hz and 30 Hz in the lateral axis. The amplitude in the vertical axis corresponds to a half sine pulse of around 6 g. The velocity change corresponds to a value of around 1 m/s.

Overall, the data appear 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.

6 Inter data source comparison

Despite the differences, already highlighted, between the vibrations arising from different aircraft types, the spectral characteristics of propeller aircraft vibration do have a degree of similarity. The background broadband random vibration appears at relatively low levels and does not vary greatly with flight condition. The responses are dominated by the presence of tonal components which occur at the shaft frequency, the blade passing frequency and their associated harmonics. It is these tonal components that make propeller aircraft vibration clearly identifiable. In this case all the aircraft considered show these classic propeller aircraft

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vibration characteristics. The frequency of the blade passing component is typically in the 70 Hz to 100 Hz range. The characteristics and severities of the aircraft considered also align with the majority of the supplementary information reviewed.

Comparing the shock characteristics is more difficult as only severities from a single aircraft are available. Nevertheless, the characteristics are essentially as would be expected from a normal landing shock (whether jet or propeller aircraft) and are not significantly different from the shocks experienced from general handling during transportation.

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 vibration excitations affecting internally carried payloads on fixed wing propeller aircraft, primarily arise from the action of the propellers. The rotating propellers generate vibration that is mechanically transmitted directly through the aircraft structure and indirectly as pressure fluctuations. These pressure fluctuations impinge on the aircraft structure, producing a structural dynamic response. Generally the maximum vibration severities experienced within the cargo bay is by payloads sited in the plane of the propellers. The dynamic response on any point on a propeller aircraft will be the sum of several sources and excitation mechanisms. A brief description of the main sources and mechanisms is as follows.

a) Mechanical imbalance: vibrations caused by mechanical imbalance of the propeller will be apparent at the shaft rotational frequency and its associated harmonics. Routine aircraft maintenance should minimize this source of dynamic excitation, but will not entirely eliminate it.

b) Propeller blade modes: propeller blade modes can be excited by forcing functions such as air moving though the propeller disc or by disc wing interaction. This can cause vibration to be transmitted through the propeller hub bearing into the aircraft structure at the discrete modal frequencies of the blades. This is unlikely to be a major source of vibration as designers will attempt to minimize blade vibration to prolong the life of the propeller.

c) Air flow interference: vibration can be induced in the propeller blades by the airflow streaming backwards from the propeller and meeting the wing and its surrounding pressure field. The vibrations occur at a characteristic frequency, dependent upon the number of interferences per revolution of each blade and the blade passing frequency. Some harmonics may be missing in measured spectra, because the resultant force acting on the blades is the vector sum of the forces acting on the whole propeller, i.e. some harmonics may add and others subtract. The significance of this source, which is only applicable when the propeller is located in front of the wing, is dependent upon the longitudinal dimension between the propeller and the wing.

d) Propeller pressure fields: the acoustic pressure field generated by rotating propellers can be considered in two regimes i.e. when a propeller develops no thrust (producing thickness noise) and when the propeller develops thrust (producing rotation noise).

   - Thickness noise is generated as a consequence of the air moving out of the way of the blade and returning when the blade has passed. The resulting pulsation of air acts as a classic noise source. When considering this mechanism, the propeller disc is seen to consist of a set of pulsating sources, with appropriate phase relationships. At the fuselage, this is perceived as a series of pressure pulses arriving at the blade passing frequency.

   - Rotation noise arises when a blade develops thrust. Additional flow noise is generated as the blade encounters disturbed air flow, from the vortices originating from the preceding blade. The rotation noise produced by the blade developing thrust cannot be determined as accurately as thickness noise. This is due in part to the complicated nature of the velocity flow field around the propeller disc.

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e) Aerodynamic flow: another source of vibration, but less significant for propeller aircraft, is that associated with the turbulence in the airflow surrounding the aircraft. The airflow over the structure may be smoothly attached to it, or it may be detached, these two conditions producing significantly different vibration excitations.

f) Vortices: vortices are shed from the rotating propeller blade tips. These vortices impinge on the adjacent aircraft structure, producing significant dynamic responses in the plane of the propeller. Vibration effects arising from vortices would not be expected to be significant for an aircraft fitted with a “pusher” propeller, because of the directional nature (directivity) of vortex noise. At certain conditions of angle of attack, side-slip and airspeed, it is possible for vortices originating from parts of the aircraft to impinge on the downstream structure. The characteristics of these vortices are such that high amplitude structural vibrations of an almost periodic nature may arise. The nature of the excitation implies that it will be transitory and rarely occurs for more than a few seconds at any one time, however, during the life of an aircraft the total number of such occurrences may be significant. The resulting vibration characteristics, severities and areas of airframe affected will be unique to aircraft type. The potentially high levels of vibration could result in low to medium cycle fatigue.

g) Propeller tip critical flow: some modern propeller aircraft utilize propeller blades which generate air flow in the transonic and supersonic region. As a consequence, shockwaves are established which extend aft of the propeller disc. These give rise to dynamic responses both in the blades and the aircraft structure. Such dynamic excitations can be severe and are particularly prevalent in the mid to high frequency ranges.

The propeller blade pressure fluctuations, impinging on the aircraft structure at the blade passing rate, result in the production of a fundamental tone and its harmonics. Both the aerodynamic flow and the power plant mechanical vibrations contribute to the aircraft structural response, in the form of a tonal and broadband excitation. The interaction of the propellers and the aircraft structure, dictate whether the blade passing fundamental or any of its harmonics exhibit the greatest dynamic response. Generally the vibration amplitudes at propeller blade passing frequencies are more significant than those produced by the engine shaft rotation. The extent to which dynamic excitation may be generated depends upon the flight condition.

The different sources of propeller aircraft vibration are each characterized by a particular pressure pattern. Propeller rotation noise is at a maximum in the plane of the propellers. Mechanical and aerodynamic imbalances also tend to be most significant close to the plane of the propellers. Effects of vortices shed from the tips of the propellers are most apparent towards the rear of the aircraft. Blade thickness noise and supersonic shock waves tend to radiate most strongly to the rear of the plane of the propellers. As a consequence aircraft dynamic responses are dependent upon location in the aircraft. The most significant vibration arises in the plane of the propeller blades, which are significantly greater than in any other location. Broadly, the amplitude of the vibration tonal components reduce with distance from the plane of the propeller blades, whilst the effects of aerodynamic excitations increase toward the rear of the aircraft.

Payloads dynamic response will depend upon its location within the aircraft cargo bay. The dynamic environmental conditions in the plane of the propeller blades are significantly greater than in any other location in the cargo bay. Broadly the vibration tonal component amplitudes reduce with distance from the plane of the propeller blades, whilst the broadband remains relatively similar.

Aircraft cargo bay floors are of a relatively light weight construction, as a consequence, the dynamic response of the floor can be influenced by the mass and footprint of an individual payload and the payload loading configuration. This cargo bay floor dynamic response will also be influenced by the payload support arrangement such as pallets, the type of payload supports (i.e. rollers, balls or flat surfaces) and the tie down arrangement (i.e. straps and nets).

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