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TECHNICAL REPORT

colour inside

Environmental conditions – Vibration and shock of electrotechnical equipment – Part 2: Equipment transported in fixed wing jet aircraft

IEC/TR 62131-2:2011(E)

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IEC Central Office
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CH-1211 Geneva 20
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Email: inmail@iec.ch
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Environmental conditions – Vibration and shock of electrotechnical equipment – Part 2: Equipment transported in fixed wing jet aircraft

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 2: Equipment transported in fixed wing jet aircraft

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IEC/TR 62131-2, which is a technical report, has been prepared by IEC technical committee 104: Environmental conditions, classification and methods of test.

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The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
104/507/DTR	104/536/RVC

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

A list of all the parts in the IEC 62131 series, 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 publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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ENVIRONMENTAL CONDITIONS – VIBRATION AND SHOCK OF ELECTROTECHNICAL EQUIPMENT –

Part 2: Equipment transported in fixed wing jet aircraft

1 Scope

IEC/TR 62131-2, which is a technical report, reviews the available dynamic data relating to electrotechnical equipment transported in fixed wing jet transport aircraft. The intent is that from all the available data an environmental description will be generated and compared to that set out in IEC 60721.

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.

This technical report primarily addresses data extracted from a number of different sources for which reasonable confidence exist as to their quality and validity. The report also presents data for which the quality and validity cannot realistically be reviewed. These data are included to facilitate validation of information from other sources. The report clearly indicates when it utilizes information in this latter category.

This technical report addresses data from several different transport aircraft[1]. Although one of these aircraft is no longer used commercially, data from it are included to facilitate validation of information from other sources.

Relatively little of the data reviewed has been made available in electronic form. To permit comparison, a quantity of the original (non-electronic) data have been manually digitized in this technical report.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60721 (all parts), *Classification of environmental conditions*

IEC 60721-3-2:1997, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation*

1 Lockheed Tristar KC Mk 1, Lockheed Tristar L-1011, BAe VC10 K, Boeing 747 Combi, McDonnel Douglas DC8 Cargo, Lockheed C5A (Galaxy), Lockheed C-141 (Starlifter), Boeing NC-135 (707) are the trade names of products supplied by Lockheed, BAe, McDonnel Douglas and Boeing, respectively. This information is given for the convenience of users of this technical report and does not constitute anendorsement by IEC of the products named.

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3 Data source and quality

3.1 Lockheed Tristar KC Mk 1

The vibration data for the Lockheed Tristar KC Mk 1 aircraft are been taken from a Lockheed report [1] [2] on a flight test carried out in support of a US DoD program. Reference [1] reports on a single flight of a Lockheed Tristar L-1011 wide body commercial aircraft which had been undertaken to record vibration data. Measurements were recorded at two positions within the aircraft for a comprehensive range of flight conditions which are set out in Table 1.

The trial aircraft was fully fitted out. Although photographic evidence is poor quality, it indicates that the aircraft had seating and [1] indicates that it had internal fixtures and fittings and was not a bare shell. The aircraft’s gross weight for the data flight was between 190 000 Kg (at take-off) and 165 000 Kg (on landing).

Measurements were made at two positions on the Lockheed aircraft as illustrated in Figure 1. The transducer positions were close to the centreline of the aircraft at fuselage stations 804 and 1 218. The centre of gravity (c of g) transducer positions are on the structure supporting the cargo bay floor whereas the forward transducers are in the roof of the cabin attached via a bracket to the aircraft structure.

The data contained in [1] seems of good quality, however, the poor quality photocopy of the original report has resulted in poor definition of some of the spectra. The electrical noise from the aircraft systems was recorded and shown to be at an acceptably low level. Bibliographic reference [1] reports that a variety of no signal data were taken to provide a measure of the noise floor of the entire instrumentation system. The noise measurement is shown in Figure 2 were made with the aircraft powered by the auxiliary power unit only.

For a number of flight conditions, (Numbers 2, 3, 7, 9 and 10 in Table 1), up to four separate recordings were taken. The set of PSDs (Figures 3 to 7) were then further reduced by presenting their average and maximum curves on one plot. This successfully demonstrated that the variation in vibration response between the separate flight recordings is small. The root mean square (r.m.s.) values computed for such cases correspond to the maximum PSD curve.

Bibliographic reference [1] states that the analysis time for each power spectral density (PSD) was at least 45 s and the analysis bandwidth was 1,272 5 Hz. These values produce a normalized random error of 13 which is generally satisfactory. Also it was reported that all the instrumentation was calibrated.

To enable the vibration responses to be overlaid on a single figure,the original data plots have been manually digitizd using up to 80 points. Where the copy of the plots was poorly defined those was simply enveloped to ensure that all the major peak responses were included in the digitizd version.

For the purposes of comparison,the data for the flight conditions were grouped into take-off and landing as well as cruise. The environment of take-off and landing includes flight conditions 2, 3, 9 and 10 (from Table 1) which are take-off, power and roll, low altitude climb, low altitude descent and touchdown. The cruise environment includes flight condition 7, high altitude cruise.

3.2 BAe VC10 K

Bibliographic reference [2] presents an assessment of vibration and shock data obtained from a flight trial carried out during April, 1985. The flight trial involved the transport of two container assemblies within a VC10 aircraft. Data gathered during the trial included

2 References in square brackets refer to the bibliography.

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measurements made at the base of the containers. The flight trial requirements and its analysis are presented in [1], [1], [5] and [6].

The trials not only included the usual benign conditions such as cruise at altitude, but also several conditions relating to emergency situations, e.g. one engine inoperative, firm landings, etc. although the scope for such emergency situations is very limited on the VC10. The full list of the various flight conditions covered during the flight is presented in Table 2.

The load configuration for the flight is shown diagrammatically in Figure 16. The payload consisted of two 1 800 Kg container assemblies. For the flight the loads were secured under normal procedures and involved lashing the load containers to the appropriate aircraft tie-down points.

Flight instrumentation consisted of 11 accelerometers, used to measure cargo hold vibration both adjacent to the airframe and at the bases of the transported containers. The airframe measurements were made on cargo floor tie-down fixtures. These being suitably firm mounting locations and available at key positions in the cargo bay. The container measurements were made at suitably rigid positions around the base of the containers, so providing a measure of vibration input. The vibration measurement sites are indicated in Figure 16.

The nature of the vibration environment is, in general, broad band random. The maximum vibration amplitudes measured at the cargo hold floor tend to occur within the 200 Hz to 600 Hz bandwidth. Consequently, the flight data have been produced in acceleration power spectral density (APSD) and acceleration-time history formats. APSD plots have been produced over the frequency range 3,25 Hz to 2000 Hz. Amplitudes from the APSDs are the result of averaging throughout a particular flight condition. Results are threfore valid for those conditions when the average properties of the data are invariant with respect to time, e.g. straight and level flight. The results of the data processing carried out are contained in [2], [1] and [1].

A statement on the accuracy of the airframe/container measuring instrumentation states that the overall tolerance is ±5,9 % with a typical value in the range ±4,0 %. The analysis resolution bandwidth was 3,25 Hz and the variance error in the range 3 % to 12 %.

To enable the vibration responses to be overlaid on a single figure the original data plots have been hand digitized using up to 80 points. Where the copy of the plots was poorly defined the poorly defined portion was simply enveloped to ensure that all the major peak responses were included in the digitized version.

No discernible shocks were observed during either normal or ‘touch-and-go' landings ([1] contains a figure demonstrating this but it is not reproducible).

Although the VC10 was originally designed and operated as a commercial passenger and freight aircraft, it is no longer operated commercially. The only known current operator is the UK military. Vibration information for this aircraft is included in this assessment because it has the potential to support the validity of data from other sources.

3.3 Boeing 747 Combi (freight and passengers)

A field study was conducted on board a Boeing 747 Combi (freight and passenger) aircraft on the route Stockholm (Arianda) via Oslo (Gardermoen) to New York (John F. Kennedy Airport) and return to Stockholm (Arianda). Shock and vibration acting on the cargo during air transportation were measured and analysed.

The study encompassed all phases of the flight, including taxiing, climbing, cruising during both calm and turbulent conditions, descent and approach, landing (including touchdown and taxiing to apron). The phases considered to be the most interesting as regards cargo-influencing vibrations and which were analysed from the field trials are as follows:

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i) taxiing;

ii) take-off;

iii) initial climb;

iv) cruise, normal conditions;

v) cruise, gusts or air pockets;

vi) descent and approach;

vii) landing (touchdown, braking and roll-out);

viii) taxiing to apron.

The field data, reported in [7], were analysed by conventional frequency analysis and modelling techniques. In order to generalize the results, flight recorder data from the field trial and from other flights are included.

The fixture with the tri-axial accelerometer test set-up was mounted on the pallet with double sided tape and was placed approximately midway of the length of the pallet, about 0,5 m from the pallet edge. A fourth, separate, vertical accelerometer was mounted near the end of the pallet, approximately 0,5 m from the corner. Mounting the transducers on the pallet rather than on the aircraft deck meant that the accelerations to which the pallet was exposed, i.e. input to the cargo, were recorded. Mounting the transducers on the cargo would have meant that the accelerations recorded were dependent on the type of cargo. Of course, the products and their weight do influence the registered signals, therefore the pallet loads chosen were 'typical'. In field trial number 1 the weight of the test pallet was 1 470 kg and in field trial number 2 the weight was 2 550 kg.

The aircraft used in the field trials, a Boeing 747, is one of the most common for freight and passenger transportation. The plane in question, Dan Viking, happened to be plane number 500 in the 747 series, and was a Combi version delivered in 1981. In both trials, the pallet was placed on the main deck to the right of and close to the centre of gravity.

The field data recorded during the trip have been computer analysed in the time and frequency domains. The frequency domain analysis was carried out using both conventional spectral analysis and autoregressive modelling techniques. The sampling frequency chosen was 100 Hz and the signal was low-pass filtered at 31,5 Hz. However, since the signal/noise ratio of the recorded signal was good, the post analysis data was compensated to allow estimates up to 50 Hz to be made. This was essentially achieved by compensating for the filtering. The number of records, each spanning 256 samples, varied depending on the length of the flight phase studied. Values for the cruise phase en route have been limited to 350 records, i.e. a sampling time of about 15 min. The window mostly used for the frequency analysis was the Blackman window. For the analysis using autoregressive modelling for the spectral estimation, the Hamming window was used.

A summary of recorded extreme values and g r.m.s. values is given in Table 5. Transducer V2 is the separate, vertical accelerometer placed on the pallet corner, V1 is the vertical accelerometer placed near the pallet centre, T is the transversal accelerometer and L is the longitudinal accelerometer; V1, T and L were located on the tri-axial test set-up. Since there are no distinct dividing lines between different flight phases, the signal characteristics together with the test protocol have been used as a means of separation. In Table 5 touchdown is represented by the first four records of the landing phase.

In Table 6 the acceleration levels that can be expected to be exceeded for more than 1 % of the test time, when normal distribution is assumed, have been calculated based on standard deviations. In this case the standard deviation should be multiplied by a factor of 2,576 according to a normal distribution table. This means that 0,5 % of the values have greater positive values and 0,5 % have greater negative values. Thus, Table 6 describes the distribution of instantaneous values.

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3.4 Supplementary data

3.4.1 General remark

The data collection exercise identified some additional relevant sets of information, which come from reputable sources, but for which the data quality could not be adequately verified. They are included here to facilitate validation of data from other sources. Care should be taken when utilizing information in this category.

3.4.2 McDonnell Douglas DC8 cargo

Information is contained within the French military specification GAM EG 13 ([1]) from the cargo hold of a DC8 cargo aircraft. Information is presented for three transducers and eight flight conditions. A summary of the severities for the eight flight conditions is presented in Table 7. Spectra for the most severe flight conditions are presented in Figures 24, 25 and 26. For the most part the data presented in [1] are of low level to the extent that the measurements appear close to the measurement system noise floor (see Figure 26).

3.4.3 Lockheed C5A (Galaxy), Lockheed C-141 (Starlifter) and Boeing NC-135 (707)

As part of an exercise in the early 1970’s to authenticate test severities for the US military specification Mil Std 810, J.T. Foley ([1]) at Sandia National Laboratories in the US undertook an extensive exercise to establish transportation severities on a number of platforms. One of those was for transportation in jet aircraft. Although the measurements encompassed three transport aircraft, C5A, C-141 and NC-135, the process adopted does not allow information from individual aircraft to be identified. Moreover, the analysis process Foley used throughout his work is relatively unique and not immediately compatible with other information presented in this assessment. Nevertheless, Foley did generated test spectra which can be usefully compared with those from other methods and sources (see Figures 27 to 30 and Tables 8 and 9).

4 Intra data source comparison

4.1 General remark

The purpose of the following paragraphs is to review each data source for self consistency. The process for evaluating the vibration data takes into account the variation of vibration due to operational usage and aircraft characteristics. The levels of confidence resulting from this review directly influences the levels of factoring and enveloping that are used when deriving environmental levels.

4.2 Lockheed Tristar KC Mk 1

From the data provided in [1], an assessment of the relative severity of different flight conditions, different positions in the cargo hold and different measurement axes has been undertaken to establish both the variability and characteristics of the vibration environment within the Tristar aircraft. This comparison is partly limited as the test only included a single flight of one aircraft and therefore no firm conclusions can be made regarding any aircraft to aircraft or flight to flight variations including different aircraft weights. Moreover, only two measurement positions were used giving only an indication of the variation of the vibration levels with respect to position within the aircraft.

4.2.1 Relative severity of flight conditions

The conditions of take-off, maximum power and roll provide the highest vibration levels and correspond to those that require the most power from the engines. Similarly the flight conditions for climb and acceleration produce APSDs with levels greater than cruise. Landing at touchdown specifically in the fore and aft direction also exhibits high levels but these are almost certainly as a result of the application of reverse thrust following aircraft touchdown.

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4.2.2 Position within the cargo hold

In general the vibration levels for the forward transducers are higher than those recorded at the centre of gravity (c of g) for the same flight condition. This is particularly apparent for the lateral responses whose r.m.s. levels are up to four times higher. Only for touchdown are the c of g r.m.s. levels higher which is due to the application of reverse thrust and hence the higher engine induced responses in the 200 Hz to 600 Hz bandwidth. The spectral characteristics of the measurements recorded at the forward position are different to those recorded at the c of g position. Figure 8 and Figure 9 as well as Figure 12 and Figure 13 show typical vibration responses at the forward and c of g measurement positions for take-off (flight conditions 2 and 3) and landing (flight conditions 9 and 10). The responses at the forward position show consistent peak responses at 35 Hz, 100 Hz, 130 Hz and 180 Hz to 250 Hz and very low responses above 250 Hz whereas the responses at the c of g are predominantly flat with peaks in the frequency range 400 Hz to 600 Hz. Figure 10 and Figure 11 show typical vibration responses at the forward and c of g measurement positions for cruise.

4.2.3 Relative severity of measurement axes

For the responses measured at the c of g, the fore and aft direction consistently exhibits the highest vibration levels due almost certainly to the transducers proximity and alignment to the engines. The vertical and lateral responses at the c of g are broadly similar. For the responses measured by the forward group the longitudinal and transverse directions provide an equal number of the highest responses. The responses in the vertical direction tend to be lower than the other directions.

4.3 BAe VC10 K

4.3.1 General remark

For the purpose of establishing trends only data originating from the airframe sites have been considered. This is because airframe vibration, being a measure of vibration input to the cargo hold floor, constitutes the most complete description of the input environment. For the purpose of trend identification discussed below, the data have been examined in terms of overall acceleration (g) r.m.s. vibration in the frequency band 3,25 Hz to 2000 Hz and are shown in Table 3. A summary of container acceleration (g) r.m.s. vibration levels in the bandwidth 3,25 Hz to 399 Hz which excludes the power supply noise components, is presented in Table 4.

4.3.2 Relative severity of flight conditions

The vibration levels recorded during cruise were very low; the maximum being 0,156 g r.m.s. at the starboard aft (vertical) location, during cruise at 11 000 m (37 000 ft) and Mach 0,83. This is depicted in the APSD plot shown in Figure 17 where it may be seen that APSD levels do not exceed 0,000 1 g^2/Hz. The maximum vibration tended to occur during take-off, descent and reverse thrust upon landing. Vibration during these short duration events was up to four times greater than that during cruise. The maximum vibration recorded during the trials was during reverse thrust after landing. In this condition 0,674 g r.m.s. was measured at the starboard aft location in the vertical axis. The corresponding maximum APSD level was 0,001 4 g^2/Hz. as may be seen in Figure 18. No discernible differences were apparent in vibration when one of the aircraft's engines was throttled right back.

4.3.3 Position within the cargo hold

The character of vibration within the cargo hold was of increasing vibration towards the rear of the aircraft where the engines are situated. This is particularly apparent during those flight conditions which demanded high power from the engines, such as take-off. In such conditions acceleration (g) r.m.s. levels recorded at the rear of the hold were around three times greater than those towards the nose.

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4.3.4 Relative severity of measurement axes

For maximum consistency, the relative severity of vibration in the three measurement axes was undertaken using data from triaxial accelerometers. Results indicate that vibration in the vertical, transverse and fore/aft axes are generally in the ratio of 1,0: 0,8: 0,3 respectively. Data originating from the forward container, however, do not conform to this pattern. This behaviour is attributed to the effects of power supply noise on the low vibration levels recorded. This view is supported by a comparison of APSDs from the forward and rear mounted containers, as shown in Figures 19 and 20. Furthermore, a comparison of acceleration (g) r.m.s. in the frequency band of 3,25 Hz to 399 Hz, presented in Table 4, which excludes noise components, does conform to expectations regarding the relative severity of axes.

4.4 Boeing 747 Combi (freight and passengers)

4.4.1 General remark

The data gathering exercise, on the 747 reported in [7], was accompanied by another exercise measuring the vibration and shock conditions during ground handling at airports. With this experience [1] precedes its review of the aircraft severities with the following observation:

> “As far as stress levels are concerned, the ground handling and ground transport phases of an air transport are the severest, next come take-off and landing. Less severe from the point of view of accelerations are phases when the aircraft is airborne.”

4.4.2 Relative severity of measurement axes

The vertical accelerations generally are the greatest. The difference between vertical acceleration at a pallet corner and vertical acceleration at the middle of the pallet is relatively small, but noticeable. This means that the vertical accelerations at the pallet corner are 'rattling'. The transverse and fore/aft accelerations are generally smaller than the vertical accelerations. The relation between them is dependent on the phase of the flight. In phases where the aircraft is markedly inclined, such as climb and descent, the fore/aft accelerations are greatest. This is also the case during the acceleration at take-off and braking after touchdown. During the cruise phase the transverse accelerations are normally somewhat larger than the fore/aft accelerations.

4.4.3 Relative severity of flight conditions

The largest maximum acceleration levels have been recorded during landing where touchdown gave 0,42 g pk in the frequency range studied.

5 Inter data source comparison

For the most part the data from the various sources not only indicates a reasonable degree of self consistency but also a fairly good degree of consistency across the various sources. None of the verified data sources is obviously significantly different from the remainder to the extent that its validity (or that of the remainder) is called into question.

The broad trends are consistent for all the aircraft addressed. Of particular note is that all the data indicates take-off to be marginally less severe than landing, but both are markedly more severe than cruise conditions. In several cases the most severe condition during landing is identified as occurring during the application of reverse thrust. The extent (and frequency range) of this condition varies, but this is not surprising given the different engine configurations of the aircraft concerned.

Two of the three good data sources indicate that responses in the vertical axis are marginally greater than transverse which in turn are slightly greater than fore/aft. Insufficient data is available to identify a definitive trend of the vibration along the length of the aircraft. Mostly

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the data coincides with the expectation that vibrations at the rear of the aircraft are more severe than at the forward locations. This being due to the boundary layers being thicker at the rear of the aircraft, the proximity of the engines and the engine jet flow.

All the data sources, with one exception, have utilized acceleration power spectral density as the means of analysing the vibration data. This approach is unquestionably valid for the analysis of cruise vibrations which not only have a broad band random characteristic (mainly originating from aerodynamic flow over the fuselage), but also are relatively stationary for sustained periods. However, the approach is not necessarily valid for the analysis of take-off and landing conditions. Whilst the entire period of these conditions is short, the responses are continuously varying with worst case conditions occurring for only a few seconds. All the data presented for take-off and landing, with the exception of Foley, are in terms of acceleration power spectral densities. However, the analysis period used vary markedly.

6 Environmental description

6.1 Lockheed Tristar KC Mk 1

The measured data constantly shows a difference in dynamic characteristics between the vibration environment from cruise and between that from take-off and landing. For that reason the environment descriptions are presented separately for take-off and landing and for cruise. Both descriptions are a compilation of all the digitized vibration spectra from all the measurement sites and measurement directions for the relevant flight conditions. Hence the environment descriptions represent the worst case measured data.

The environment vibration description for cruise is given in Figure 14. It includes all the spectra produced from the data recorded during flight condition 7.

The environmental vibration descriptions for take-off and landing are given in Figure 15. It includes all the spectra produced from the data recorded during flight conditions 2, 3, 9 and 10. As it includes data for both the forward and c of g measurement sites it includes the peak responses at the frequencies 35 Hz, 100 Hz, 130 Hz and 180 Hz to 250 Hz from the data measured at the forward position and also the high responses in the frequency range 400 Hz to 600 Hz from the data measured at the c of g.

6.2 BAe VC10 K

Environment descriptions, in terms of a set of worst case vibration spectra, have been compiled by overlaying APSDs during all flight conditions. The resulting spectra are shown in Figure 21. No environment description for shock conditions are presented as there was none perceivable in the measurements.

6.3 Boeing 747 Combi (freight and passengers)

No vibration or shock environmental descriptions were derived or presented in [1].

7 Supplementary data

7.1 General remark

The data collection exercise has identified two relevant sets of information which come from reputable sources, but for which the data quality could not be adequately verified. They are included here to facilitate validation of data from other sources but care should be taken when utilizing information in this category.

7.2 McDonnell Douglas DC8 Cargo

No environmental descriptions were derived or presented in [8].

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7.3 Lockheed C5A (Galaxy), Lockheed C-141 (Starlifter) and Boeing NC-135 (707)

The composite environmental descriptions for these aircraft are derived from vibration analysis inconsistent with the others in this assessment. An envelope of Foley's environmental description for vibration is presented in Figure 27. This represents the one standard deviation level of the response after been passed through a range of band pass filters (for a full discussion on the process Foley used see [9]). A landing shock identified by Foley is shown in Figure 28. From the environmental description Foley derived test severities for take-off and landing (Figure 29 and Table 3 as well as cruise (Figure 30 and Table 10). The test descriptions are in the form of a broad band random test onto which a number of discrete sine components superimposed. The rationale for this is unclear and the frequency of these components appear to relate to that of aircraft power supplies and their harmonics.

8 Comparison with IEC 60721

Broadly the identified data sources indicate a maximum spectral value during cruise of 0,001 g^2/Hz rising to 0,005 g^2/Hz at take-off/landing. The highest r.m.s. value observed, on the aircraft floor was 0,67 g. However, this was observed close to the engines during the application of reverse thrust. A more typical highest r.m.s. value on the aircraft floor was 0,35 g and about half this value on packages. Whilst, detailed spectral content varies across sources and location, the aircraft floor responses could be typified by a broad band spectrum flat from approximately 10 Hz to 1 000 Hz. The responses on packages are almost entirely below 100 Hz (although the exact frequency is presumable dependant on the dynamic characteristics of the individual package).

The severities of IEC 60721-3-2:1997, Table 5, environmental category b) (stationary vibration random) and Table 5 environmental category c) (non-stationary vibration including shock), both illustrated here in Figure 29 and Figure 30, encompass a variety of transportation conditions as well a transportation by jet aircraft. Transportation by jet aircraft is encompassed by all three dynamic classification groups included in IEC 60721-3-2. Comparison with the data collected for this exercise indicates that IEC 60721-3-2 correctly groups jet air transport under the category stationary vibration random. Moreover, the "real world" observed severities are encompassed by the vibration severities of IEC 60721-3-2:1997, Table 5, environmental category b) classes 2M1, 2M2 and 2M3. With that said, the acceleration power spectral density values are all markedly greater those noted in the data reviewed for jet air transport. IEC 60721-3-2:1997, Table 5, environmental category b) values are between 10 and 100 times greater than the worst cases observed.

None of the data reviewed identified shocks of any real note and none remotely approaching those of IEC 60721-3-2:1997, Table 5, environmental category c) (non-stationary vibration including shock). This is not particularly surprising as [7] noted "A far as stress levels are concerned, the ground handling and ground transport phases of an air transport are the severest. Next come take-off and landing, less severe from the point of view of accelerations are phases when the aircraft is airborne".

An argument could be made that IEC 60721-3-2:1997, Table 5, environmental category c) (non-stationary vibration including shock) also includes take-off and landing. If this is intended, then the shape of the test severities (Figure 30) is not ideal to encompass such conditions. Although take-off and landing are transitory conditions they contain a significant amount of vibration and contrary to the title of IEC 60721-3-2:1997, Table 5, environmental category c) (non-stationary vibration including shock), the severities represent a simple shock pulse rather than non-stationary vibration.

In addition to IEC 60721-3-2, the identified data sources can also be compared with a number of other environmental test severities for equipment transported in jet aircraft. The test severities from Foley are shown in Figure 27, Figure 28 and those from ASTM D 4728-91, Mil Std 810 issue F and G, AECTP 400 and Def Stan 00-35 are shown in Figure 33 to Figure 36, respectively. These test severities are particularly notable for the large amount of variation that they exhibit. Mostly the test spectra appear to represent conditions on the aircraft floor,

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although, one of the AECTP severities and (apparently) the ASTM D 4728-91 test severity represent the responses observed on packages. Of the test specifications reviewed only ASTM D 4728-91 is intended for non-military purposes. As a test severity for packages it appears reasonable, but the limited frequency range would make it inadequate as a representation of conditions on the aircraft floor.

No explanation is apparent why so much variation exists between the various test specifications. Most test severities will include a test conservatism factor to account for measurement variations, etc. In this case, no information is available as to the size of the factors included. One reason that could be suggested for the large variations is that as the severities are mainly based upon take-off and landing measurements, due to their short durations, these may be difficult to ascertain accurately.

Only in the case of the Def Stan 00-35 severity is the test duration related to usage. In this case, a test duration of 1 h is intended to encompass 6 h of flight. As already noted, the most severe vibrations occur for a few seconds at take-off and landing. Severities during cruise are typically less than one-fifth the take-off and landing amplitudes. On this basis, the Def Stan 00-35 test duration appears extremely conservative.

Although not claiming to be a detailed work, as part of this assessment has been undertaken to establish equivalent test durations, basic considerations indicate that test durations should be quite short. As already highlighted, the most severe vibrations occur during take-off and landings. These periods of vibrations occur for no more than 30 s to 60 s per flight. The vibration severities occurring during cruise are markedly lower than those for take-off and landing, but, potentially occur for many hours per flight. If vibration test levels are set by the amplitudes for take off and landings then 60 s of test would induced similar damage as around 50 h of flight. Consequently, as a rough estimate, a typical flight could be represented by one to two minutes of testing, provided the amplitudes are based upon the vibrations that occur during take-off and landing.

9 Recommendations

Good data has been identified from three sources, for which a reasonable amount of information is available and by which data validity can be established. Two additional data sources have been identified which come from reputable sources but for which the available information is insufficient for the data quality to be adequately verified.

For the most part, the data from the various sources not only indicates a reasonable degree of self consistency but also a fairly good degree of consistency across the various sources. None of the data sources are obviously significantly different from the remainder, to the extent that their validity (or that of the remainder) is called into question.

The broad trends are consistent for all the aircraft addressed. Of particular note is that all the data indicate take-off to be marginally less severe than landing, but both are markedly more severe than cruise conditions. In several cases, the most severe condition during landing is identified as occurring during the application of reverse thrust. The extent (and frequency range) of this condition varies, but this is not surprising given the different engine configurations of the aircraft concerned.

The severities of IEC 60721-3-2:1997, Table 5, environmental category b) (stationary vibration random) encompass a variety of transportation conditions as well a transportation by jet aircraft.

Comparison with the data collected for this exercise indicates that IEC 60721-3-2 correctly groups jet air transport under the category stationary vibration random. Moreover, the “real world” observed severities are all encompassed by the vibration severities of IEC 60721-3-2:1997, Table 5, environmental category b) classes 2M1, 2M2 and 2M3. With that said, the acceleration power spectral density values are all markedly greater those noted in the data reviewed for jet air transport.

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None of the data reviewed identify shocks of any real note and none remotely approaching those of IEC 60721-3-2:1997, Table 5, environmental category c) (non-stationary vibration including shock). With that said, it is expected that the most severe shocks will arise during the ground handling and ground transport phases of air transport.

The identified data sources indicate severities markedly lower than those currently contained in a number of test specifications. The ASTM D 4728-91 air transportation spectrum appears the most appropriate of the test severities reviewed to encompass the responses observed on packages.

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Table 1 – Tristar flight conditions and measured r.m.s. values

	Comparative r.m.s. values (g)					
	Aircraft forward accelerometers (Station 800)			Aircraft centre of gravity accelerometers (Station 1216)		
Flight condition	Vertical	Transverse	Fore-aft	Vertical	Transverse	Fore-aft
No signal (noise)	0,004	0,011	0,005	0,007	0,005	0,014
1 – Taxi	0,034	0,036	0,048	0,035	0,017	0,035
2 – Take off, power and roll	0,247	0,222	0,345	0,114	0,109	0,128
3 – Low altitude climb	0,153	0,300	0,207	0,085	0,073	0,144
4 – Low altitude acceleration	0,068	0,077	0,111	0,053	0,038	0,082
5 – High altitude climb	0,085	0,163	0,122	0,084	0,042	0,111
6 – High altitude acceleration	0,084	0,217	0,142	0,082	0,056	0,142
7 – High altitude cruise	0,120	0,224	0,152	0,086	0,059	0,150
8 – High altitude descent	0,080	0,168	0,119	0,071	0,046	0,121
9 – Low altitude descent	0,168	0,130	0,214	0,079	0,074	0,111
10 – Touchdown	0,114	0,127	0,171	0,119	0,144	0,4 49

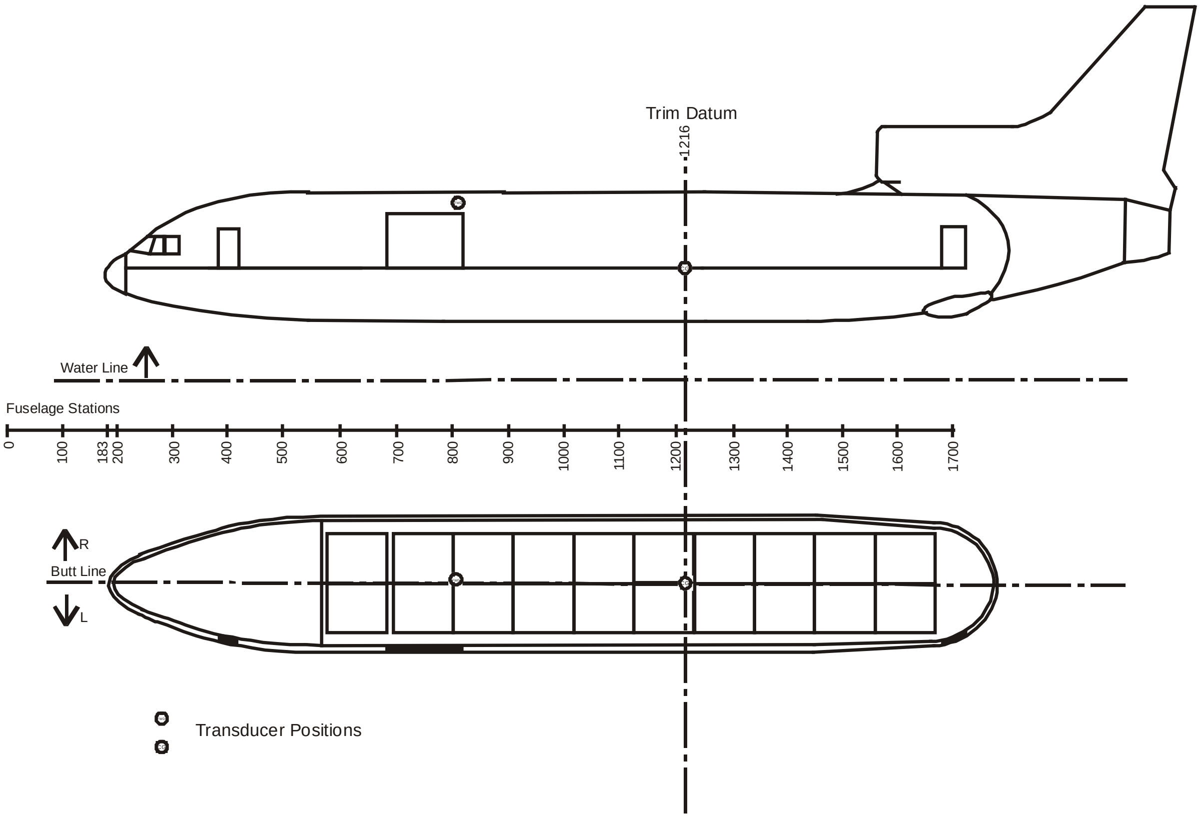

Figure 1 – Schematic of Tristar aircraft

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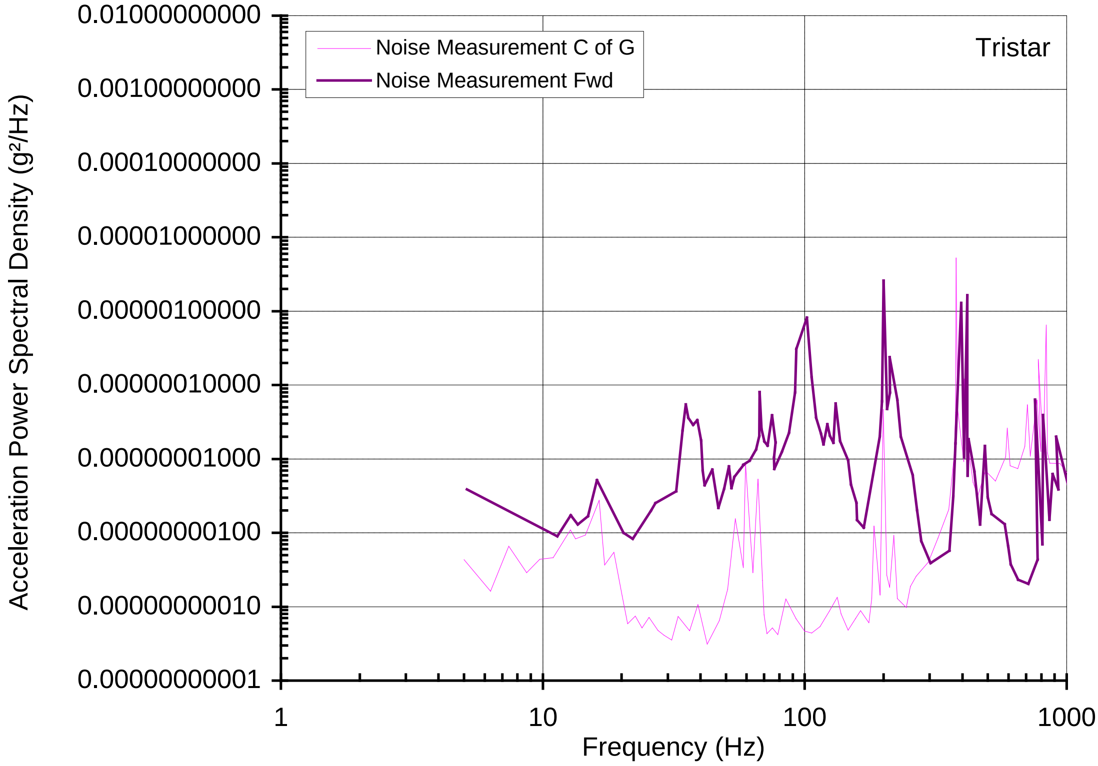

Figure 2 – Tristar noise measurements

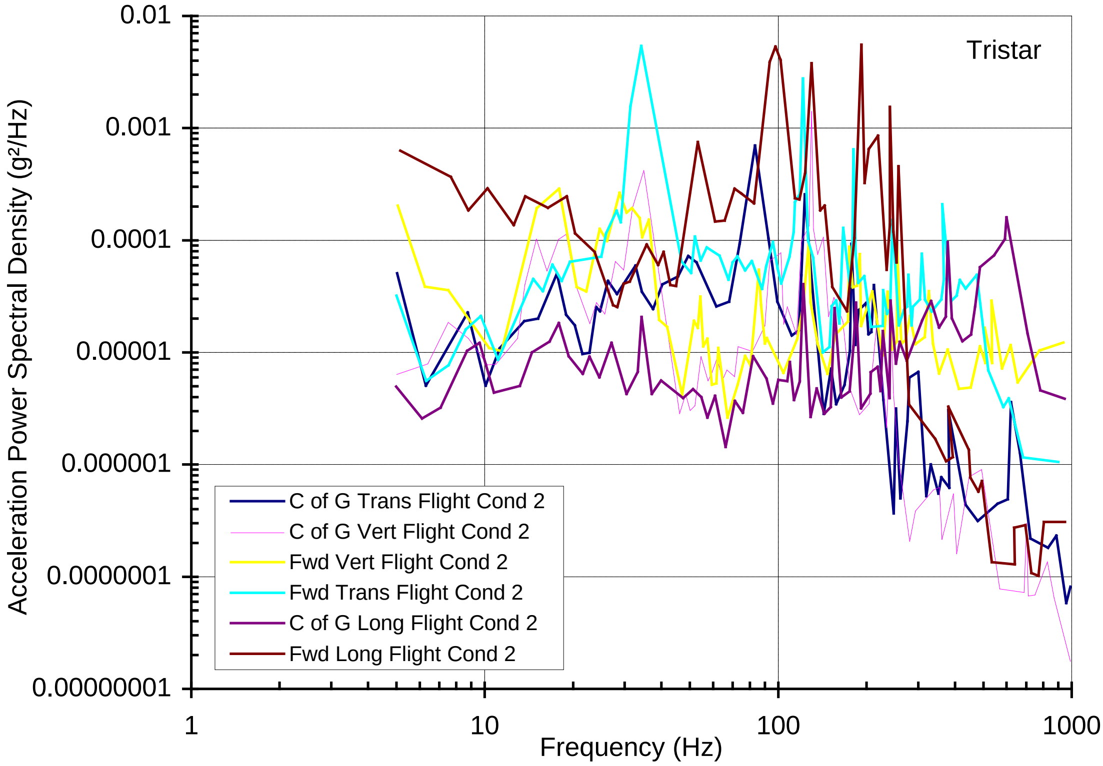

Figure 3 – Tristar vibration measurements – Take-off, power and roll

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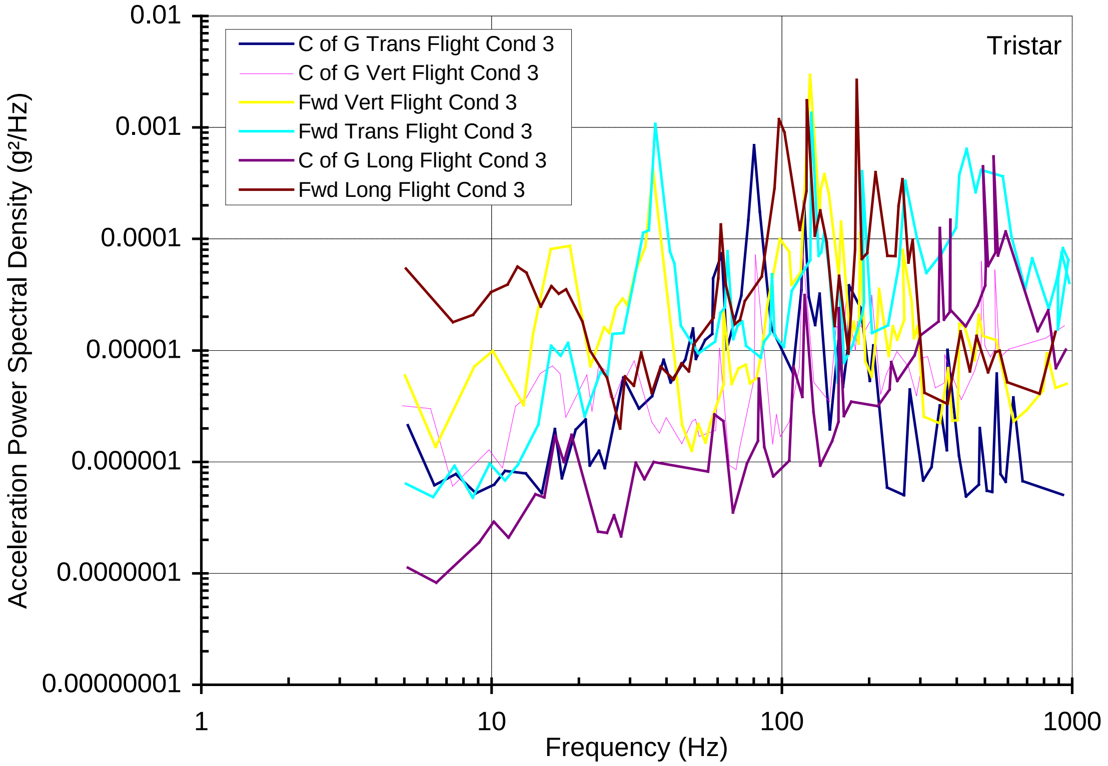

Figure 4 – Tristar vibration measurements – Low altitude climb

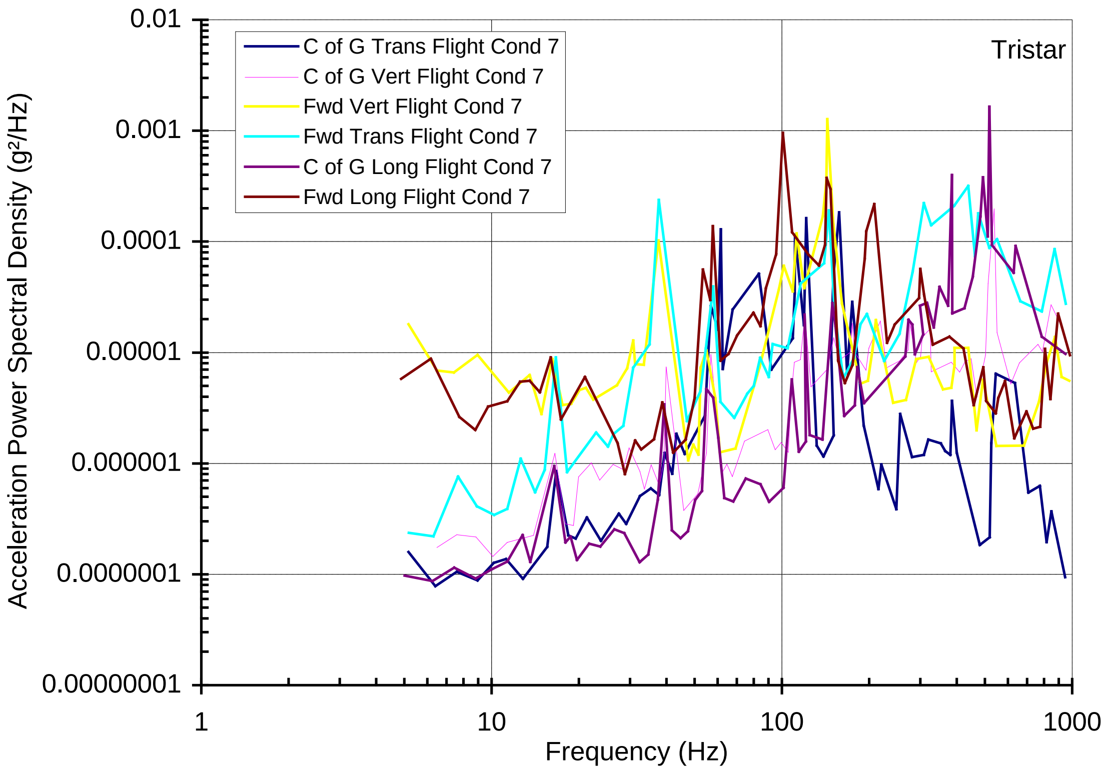

Figure 5 – Tristar vibration measurements – High altitude cruise

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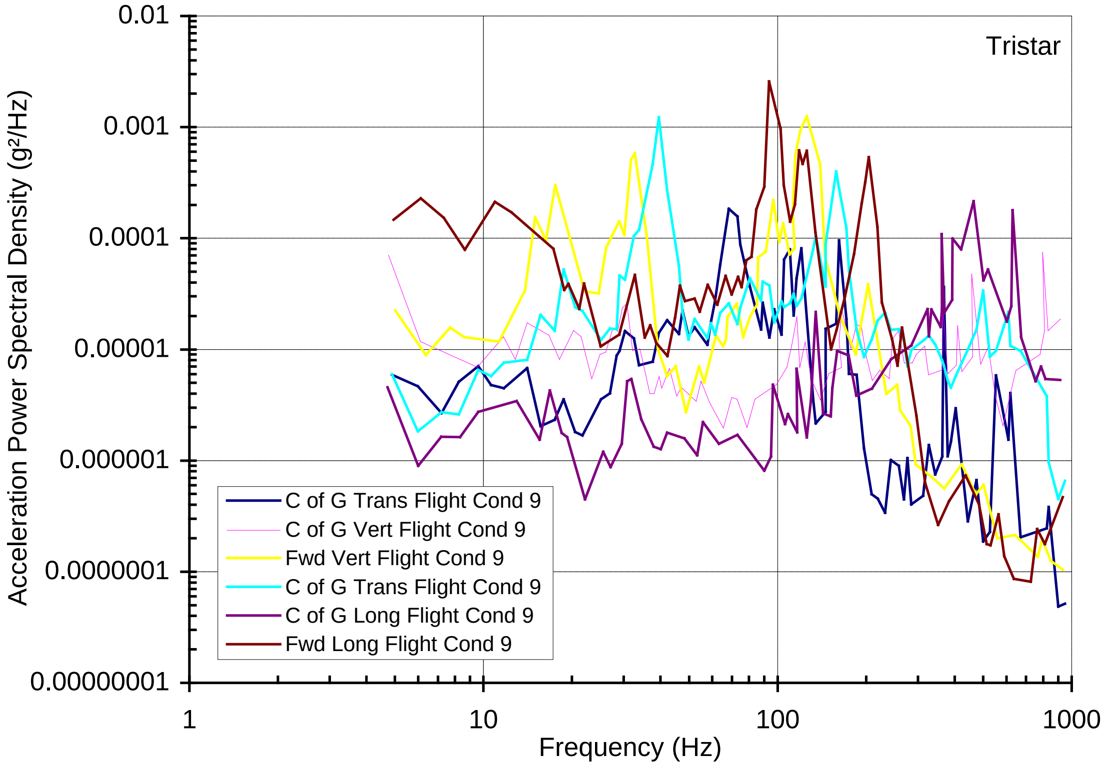

Figure 6 – Tristar vibration measurements – Landing

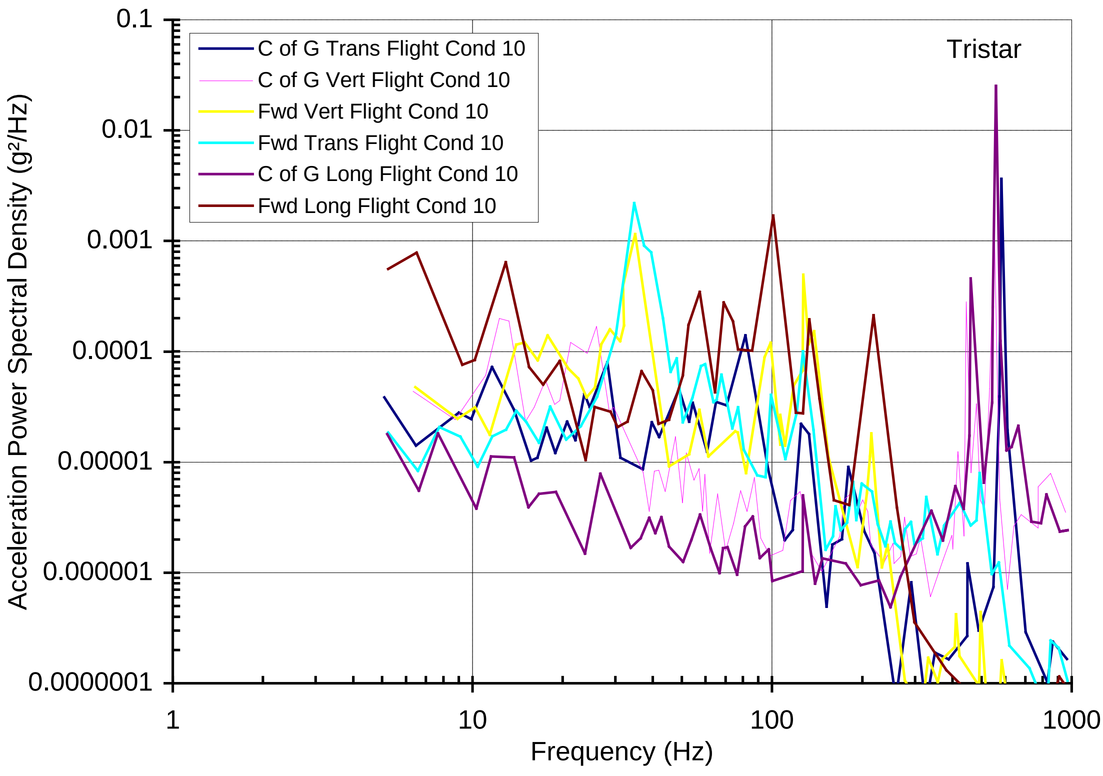

Figure 7 – Tristar vibration measurements – Low altitude decent

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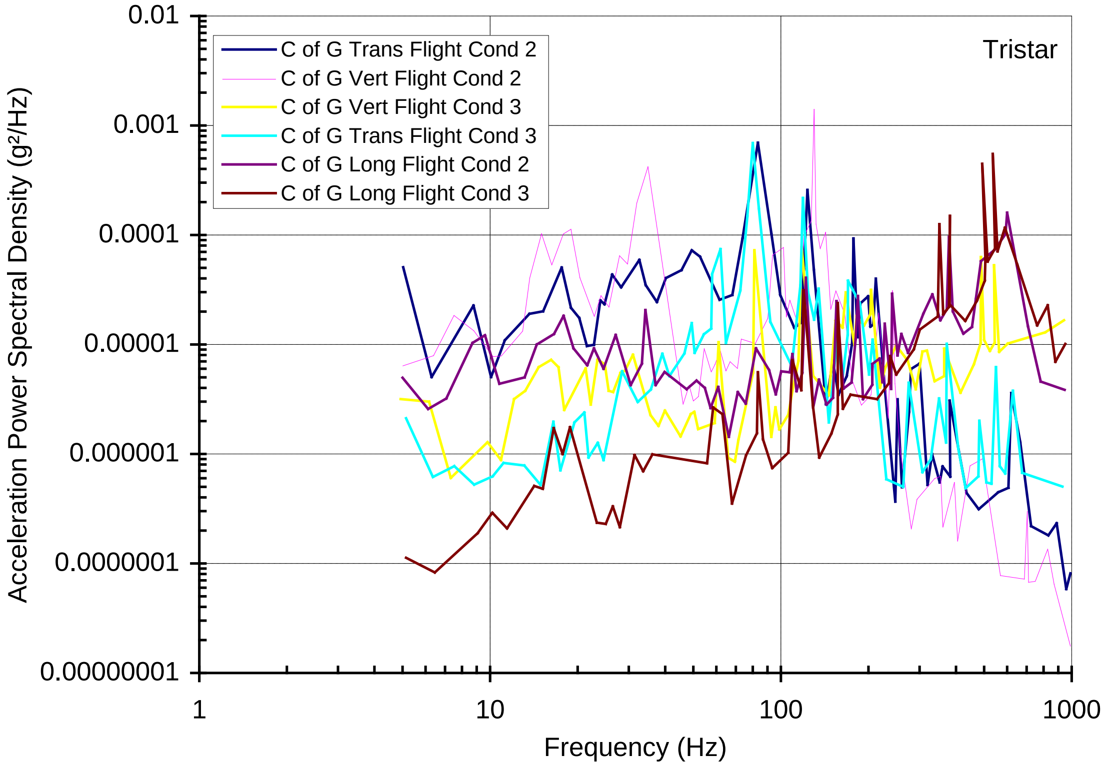

Figure 8 – Tristar vibration measurements – C of G take-off/climb

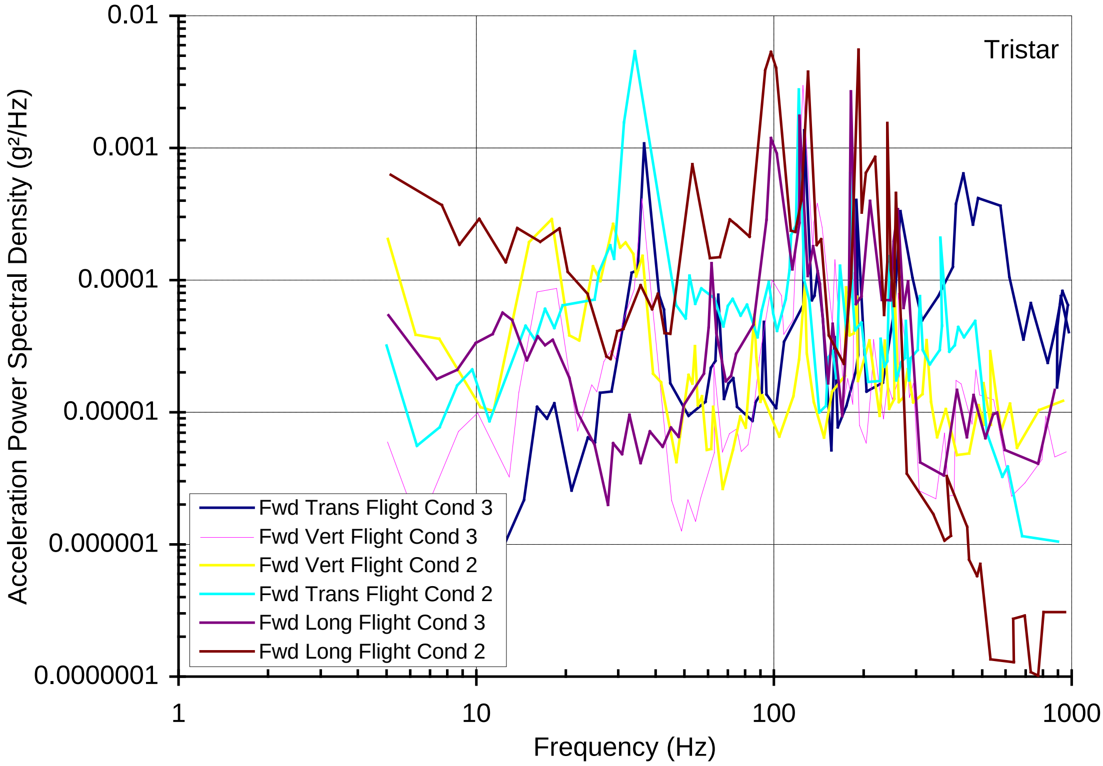

Figure 9 – Tristar vibration measurements – Forward take-off/climb

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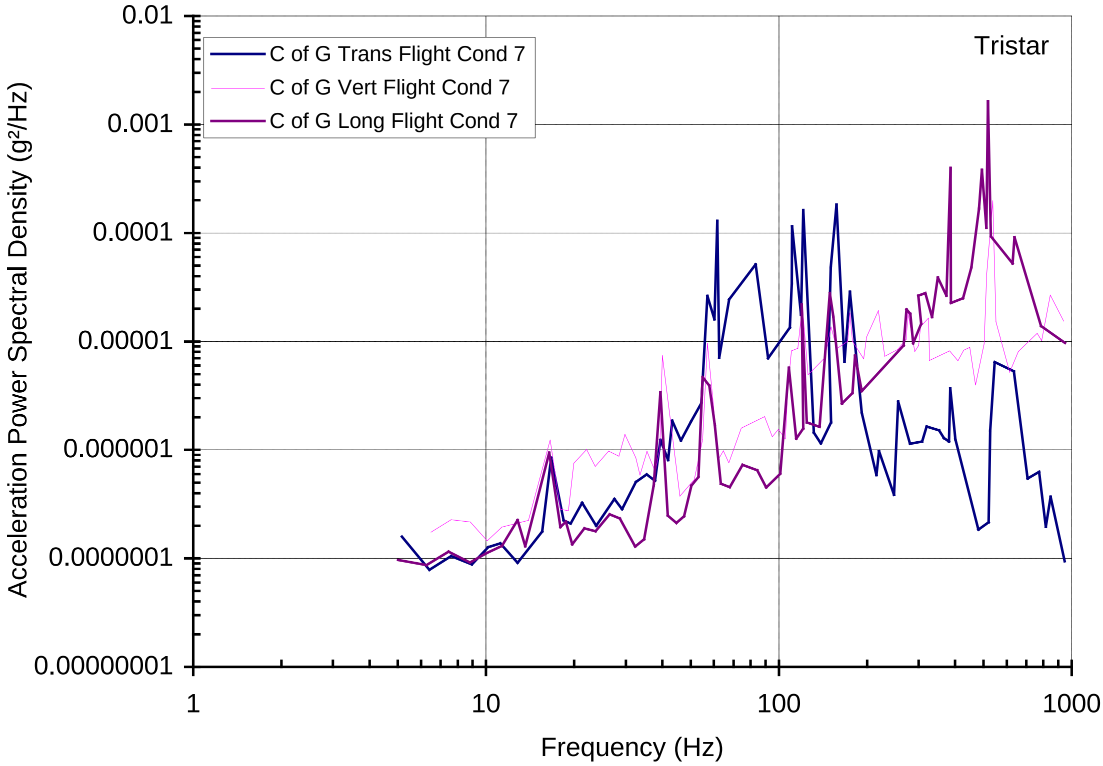

Figure 10 – Tristar vibration measurements – Centre of gravity cruise

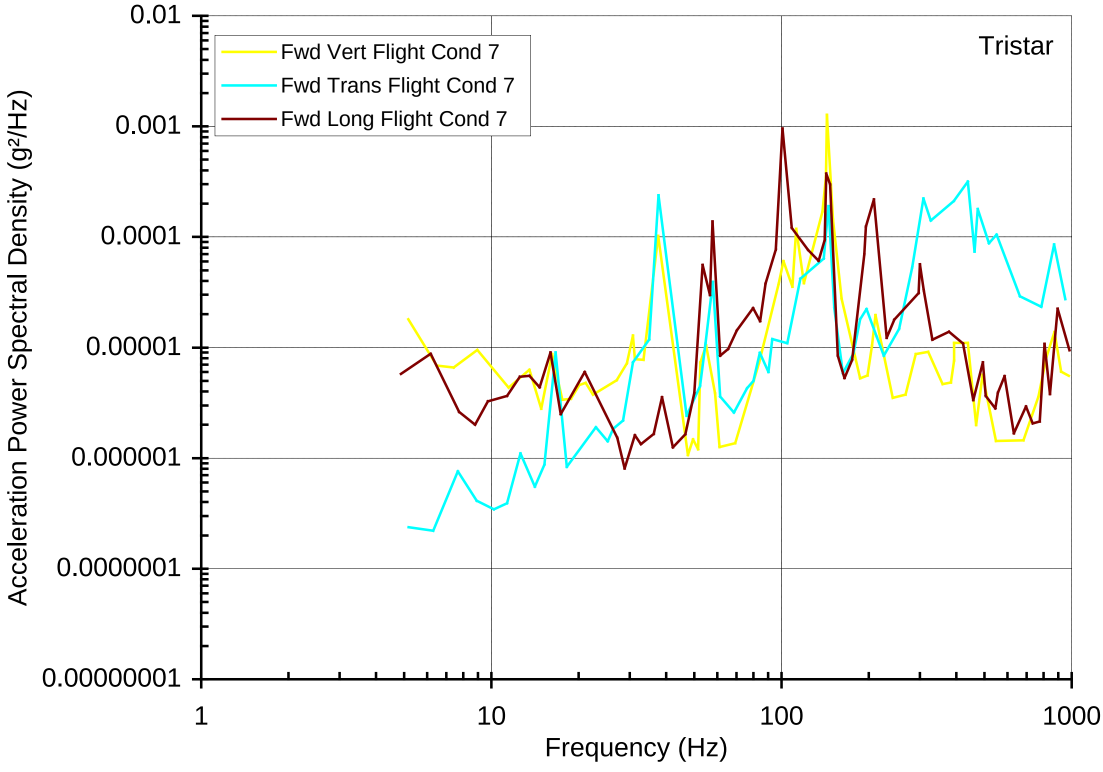

Figure 11 – Tristar vibration measurements – Forward cruise

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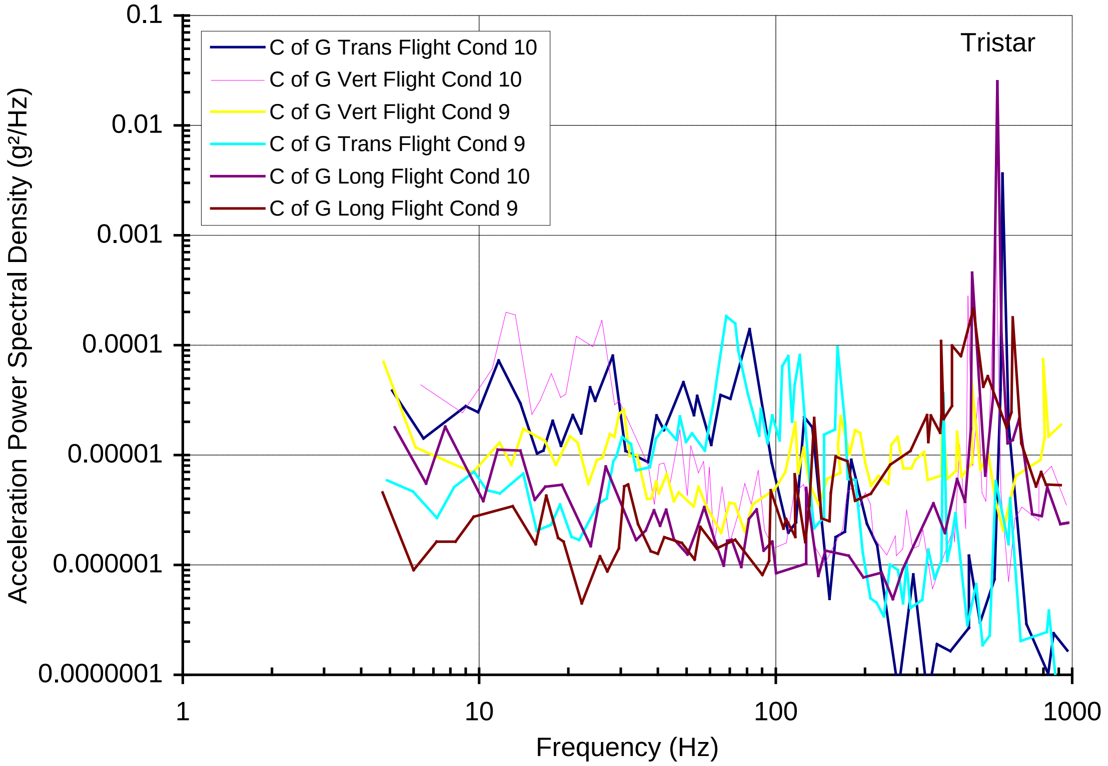

Figure 12 – Tristar vibration measurements – Centre of gravity landing

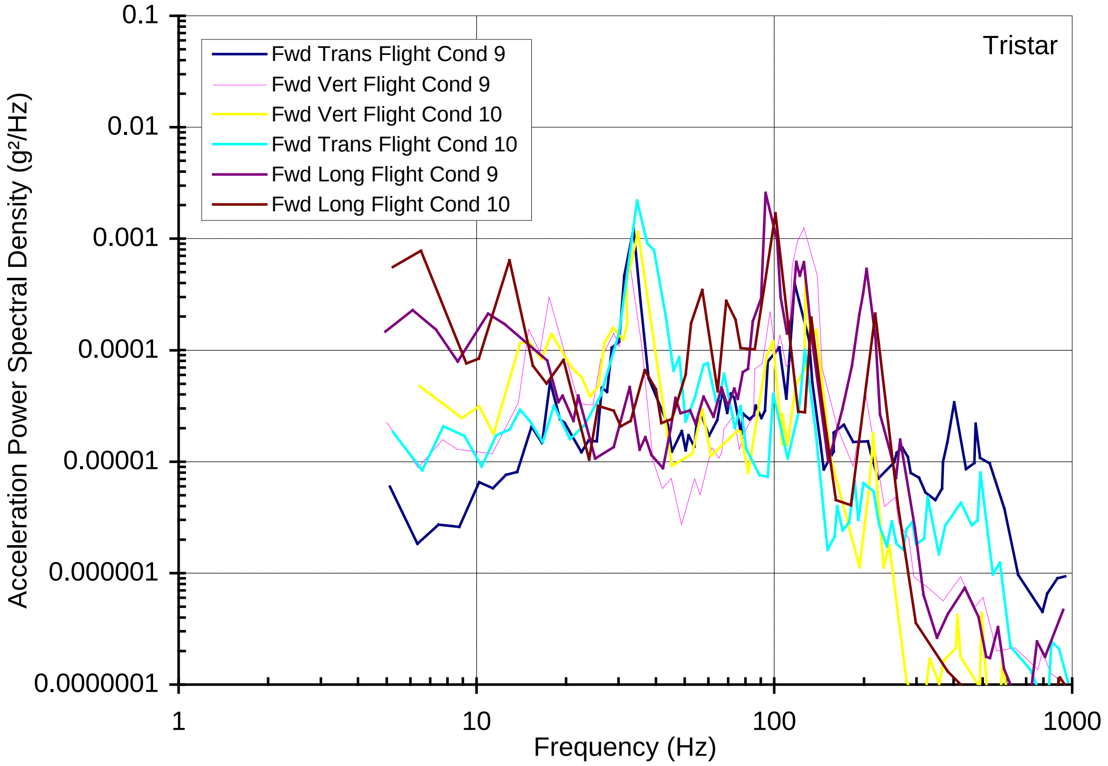

Figure 13 – Tristar vibration measurements – Forward landing

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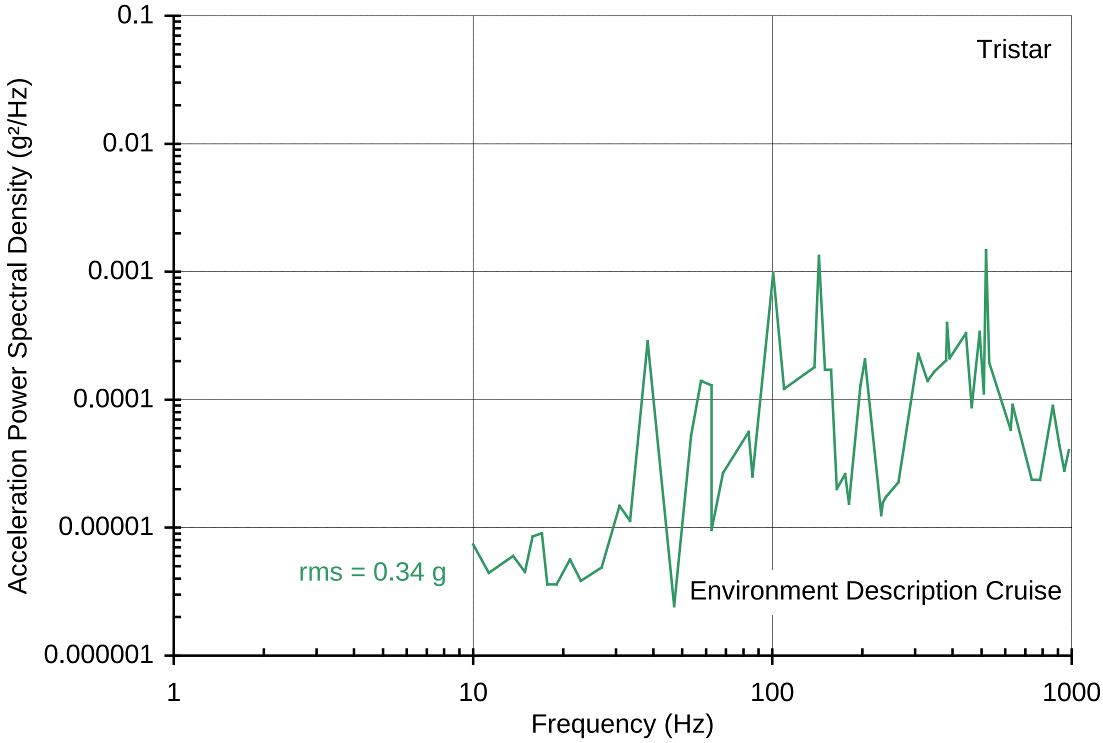

Figure 14 – Tristar vibration measurements – Cruise environment

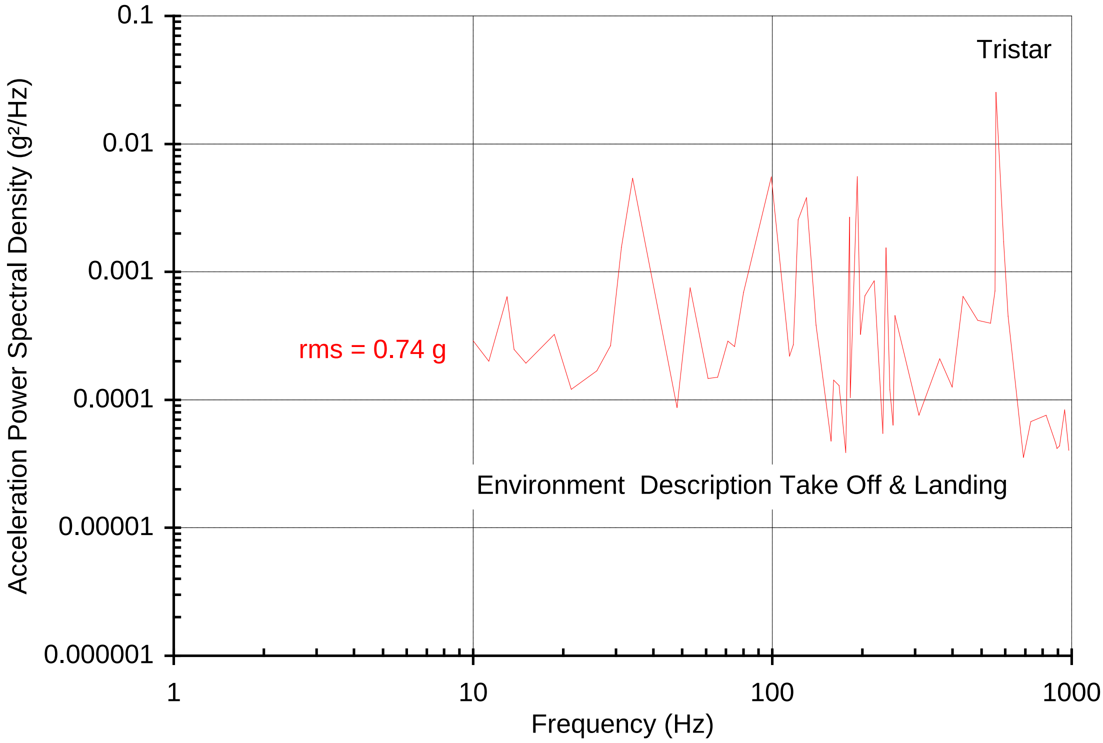

Figure 15 – Tristar vibration measurements – Take-off/landing environment

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Table 2 – VC10 flight conditions

Flight conditions monitored during the trial	
Flight condition	**Comment**
Take-off	
Climb	
Cruise	11 000 m (37 000 ft) straight and level at Mach 0,83 M
Descent	With air brakes deployed
Landing	Including normal and 'roller-touch-go'
Reverse thrust	

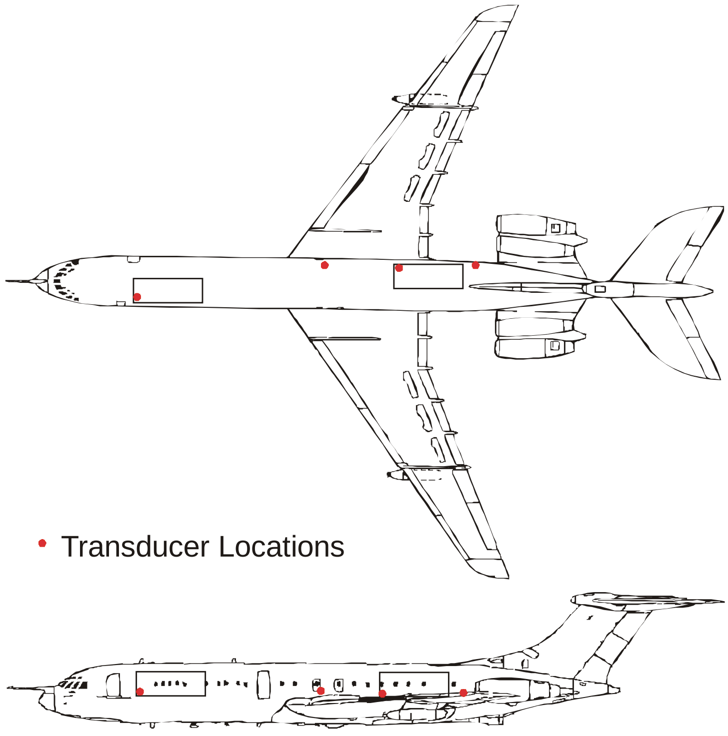

Figure 16 – Schematic of VC10 aircraft

Table 2a – VC10 measurement locations

Container measurements		Airframe measurements	
Forward container	Vertical	Main spar (frame H-698)	Vertical
Forward container	Transverse	Main spar (frame H-698)	Transverse
Forward container	Fore-aft		
Rear container	Vertical	Rear (frame H-1099)	Vertical
Rear container	Transverse	Rear (frame H-1099)	Transverse
Rear container	Fore-aft	Rear (frame H-1099)	Fore-aft

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Table 3 – Overall g r.m.s. (3,25 Hz to 2 000 Hz) for VC10 airframe/container

Location	Take-off	Climb	Cruise	Descent	Reverse thrust
Airframe					
Starboard aft (vert)	0,393	0,173	0,155	0,274	0,665
Starboard aft (Lat)	0,238	0,146	0,139	0,185	0,107
Starboard aft (fore/aft)	0,134	0,076	0,05	0,074	0,239
Starboard main spar (vert)	0,13	0,109	0,151	0,158	0,211
Starboard main spar (lat)	0,079	0,069	0,084	0,092	0,139
Starboard main spar (fore/aft)	0,064	0,052	0,058	0,065	0,096
Rear container					
Starboard fwd (vert)	0,144	0,106	0,107	0,166	0,178
Starboard fwd (lat)	0,117	0,095	0,096	0,109	0,125
Starboard fwd (fore/aft)	0,061	0,043	0,045	0,055	0,071
Fwd container					
Starboard fwd (vert)	0,107	0,089	0,088	0,094	0,108
Starboard fwd (lat)	0,177	0,153	0,153	0,162	0,178
Starboard fwd (fore/aft)	0,117	0,059	0,058	0,085	0,136

These above values include contributions from aircraft power supply noise at 400 Hz, 800 Hz, 1 200 Hz, etc. Hz. Alternative values, using only data up to 399 Hz, and so avoiding noise contributions, is shown in Table 4.

Table 4 – Overall g r.m.s. (3,25 Hz to 399 Hz) for VC 10 container measurements

Location	Take-off	Climb	Cruise	Descent	Reverse thrust
Rear container					
Starboard fwd (vert)	0,097	0,04	0,036	0,129	0,141
Starboard fwd (lat)	0,069	0,036	0,035	0,059	0,08
Starboard fwd (long)	0,043	0,019	0,018	0,036	0,055
Forward container					
Starboard fwd (vert)	0,105	0,024	0,021	0,065	0,122
Starboard fwd (lat)	0,087	0,052	0,047	0,057	0,084
Starboard fwd (long)	0,059	0,036	0,028	0,039	0,062

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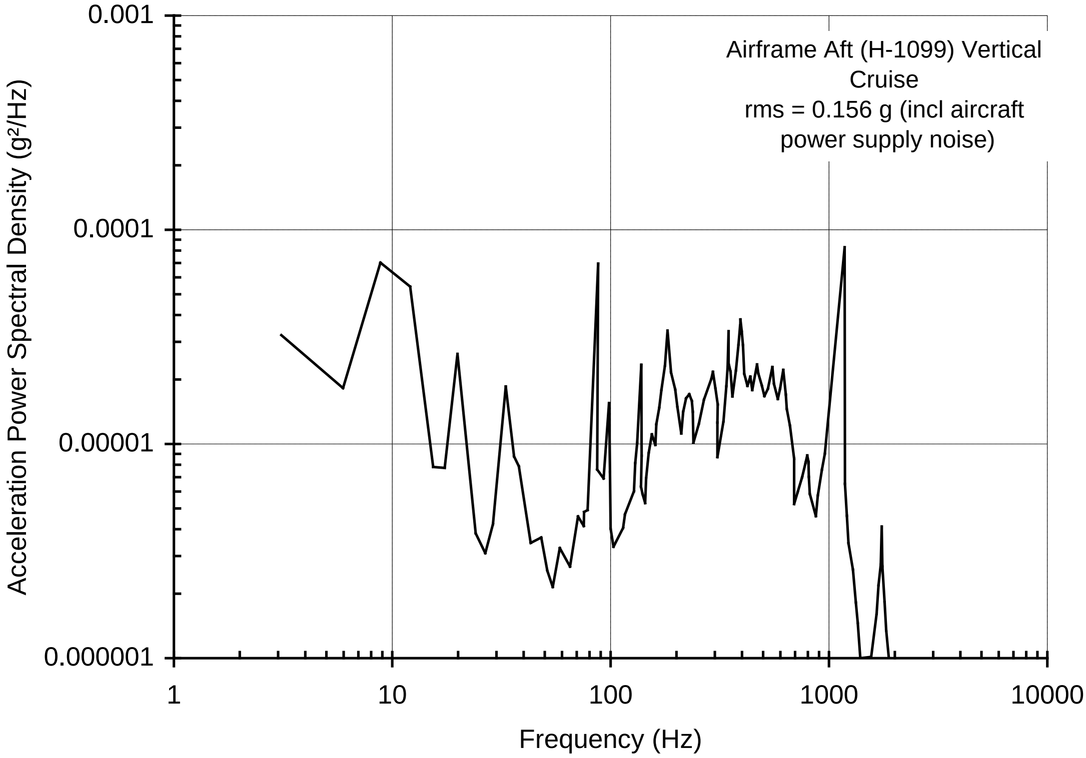

Figure 17 – VC10 vibration measurements – Cruise

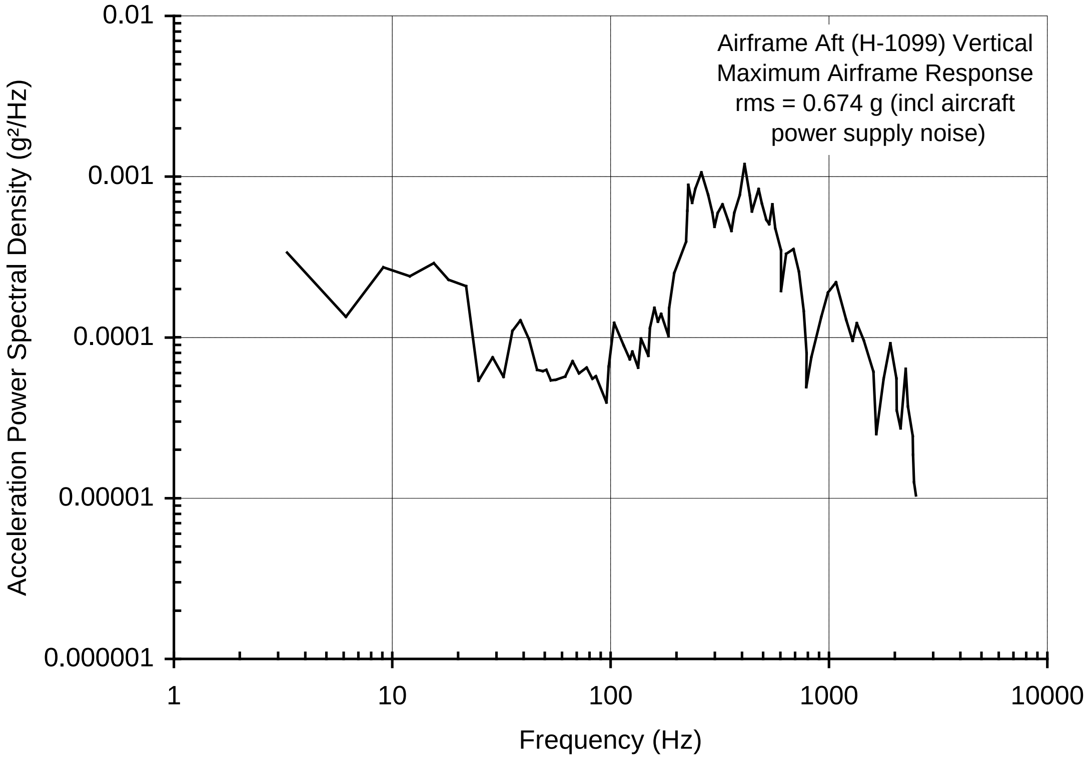

Figure 18 – VC10 vibration measurements – Maximum airframe severity

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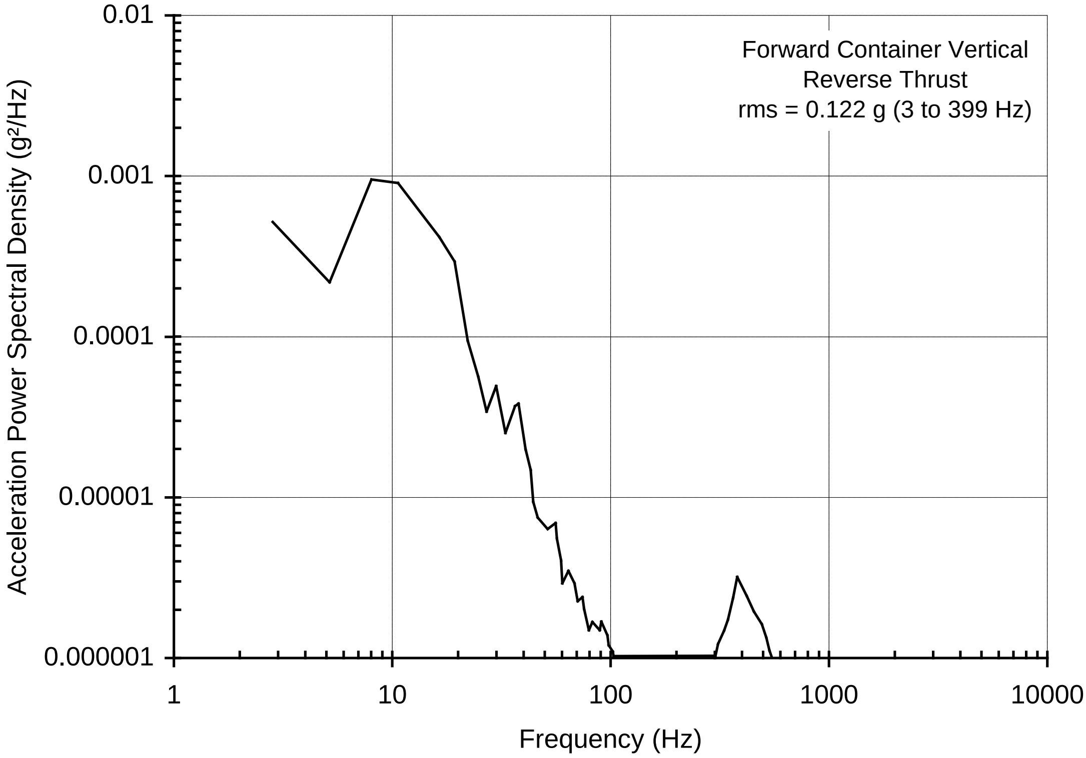

Figure 19 – VC10 vibration measurement – Forward container during reverse thrust

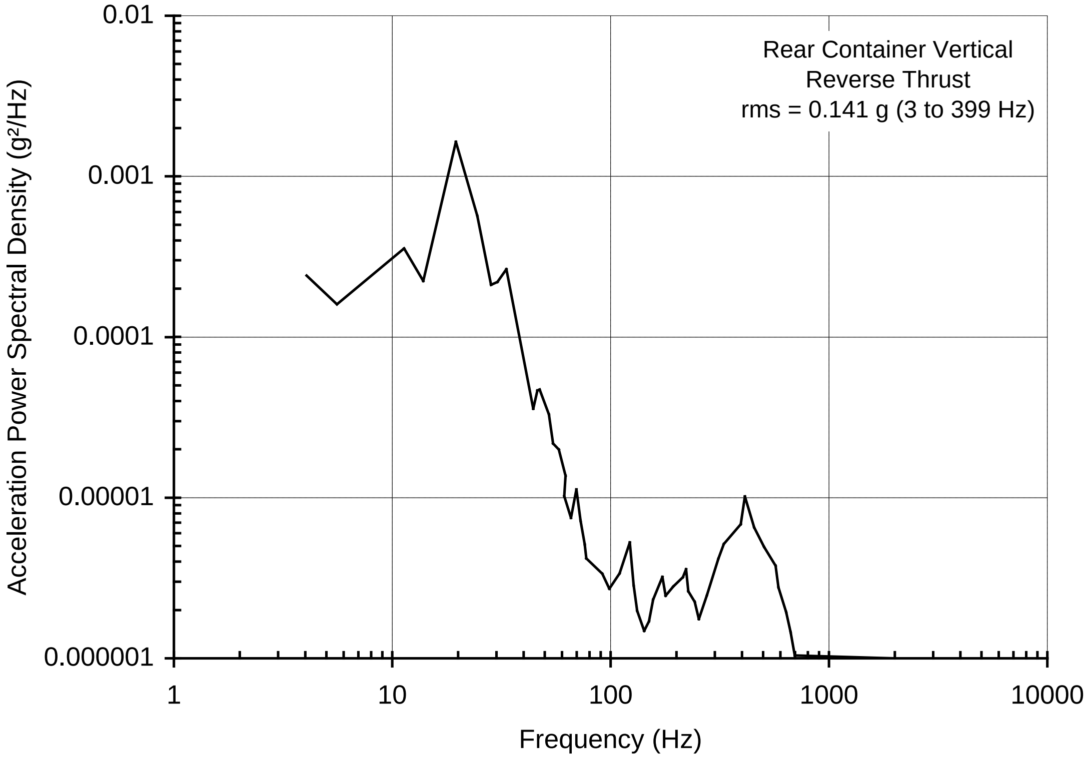

Figure 20 – VC10 vibration measurement – Rear container during reverse thrust

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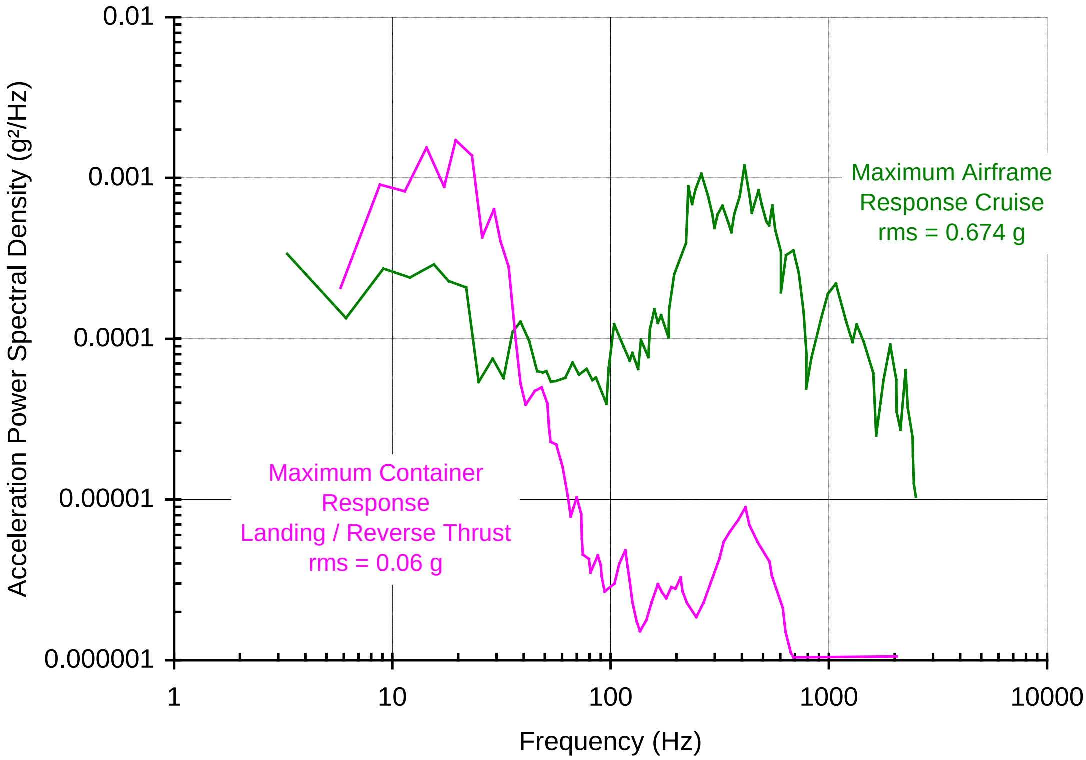

Figure 21 – VC10 measurements – Overlaid worst case spectra

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Table 5 – Summary of 747 air transport data

Flight phase	Location	Maximum values (g) for transducer				Root-mean-square g (x 10^{-3} g) transducer				Number of records
		V1	V2	T	L	V1	V2	T	L	
Taxiing	JFK[a]	0,26	0,24	0,15	0,1	26,2	24	19,3	16,2	150
Take-off	JFK	0,38	0,38	0,14	0,2	70,1	67,6	33,5	60,2	20
Climb	JFK	0,2	0,19	0,19	0,15	33,8	34,9	10,8	52,9	462
Cruise normal		0,05	0,05	0,04	0,03	9,3	10,6	6,5	5,4	350
Cruise turbulent		0,16	0,16	0,07	0,04	38	38,5	12,7	7,5	20
Descent	GEN[b]	0,21	0,21	0,08	0,14	36,5	37,9	15,8	55,5	297
Landing	GEN	0,42	0,42	0,29	0,41	79,6	85,4	62,3	89,9	
Touchdown	GEN	0,42	0,42	0,29	0,42	113	118	93,3	91,2	4
Taxiing to apron	GEN	0,08	0,09	0,1	0,12	17,6	20,3	32,1	34,7	64

[a] JFK: John F. Kennedy.
[b] GEN: Gardermoen.

Table 6 – Summary of 747 acceleration levels (g) expected to be exceeded for 1 % of the time of the trial

Flight phase	Location	Acceleration levels (g) expected to be exceeded for 1% of the time of the trial transducer			
		V1[a]	V2[b]	T[c]	L[d]
Taxiing	JFK[e]	0,07	0,06	0,05	0,04
Take-off	JFK	0,18	0,17	0,09	0,16
Climb	JFK	0,09	0,09	0,03	0,14
Cruise normal		0,02	0,03	0,02	0,01
Cruise turbulent		0,1	0,1	0,03	0,02
Descent	GEN[f]	0,09	0,1	0,04	0,14
Landing	GEN	0,21	0,22	0,16	0,23
(Touchdown)	GEN	0,29	0,3	0,24	0,23
Taxiing to apron	GEN	0,05	0,05	0,08	0,09

[a] Transducer V1 is the vertical accelerometer placed near the pallet centre

[b] Transducer V2 is the separate, vertical accelerometer placed on the pallet corner.

[c] T is the transverse accelerometer

[d] L the fore/aft accelerometer

[e] JFK: John F. Kennedy.

[f] GEN: Gardermoen.

NOTE V1, T and L were located in the tri-axial set-up. 1.

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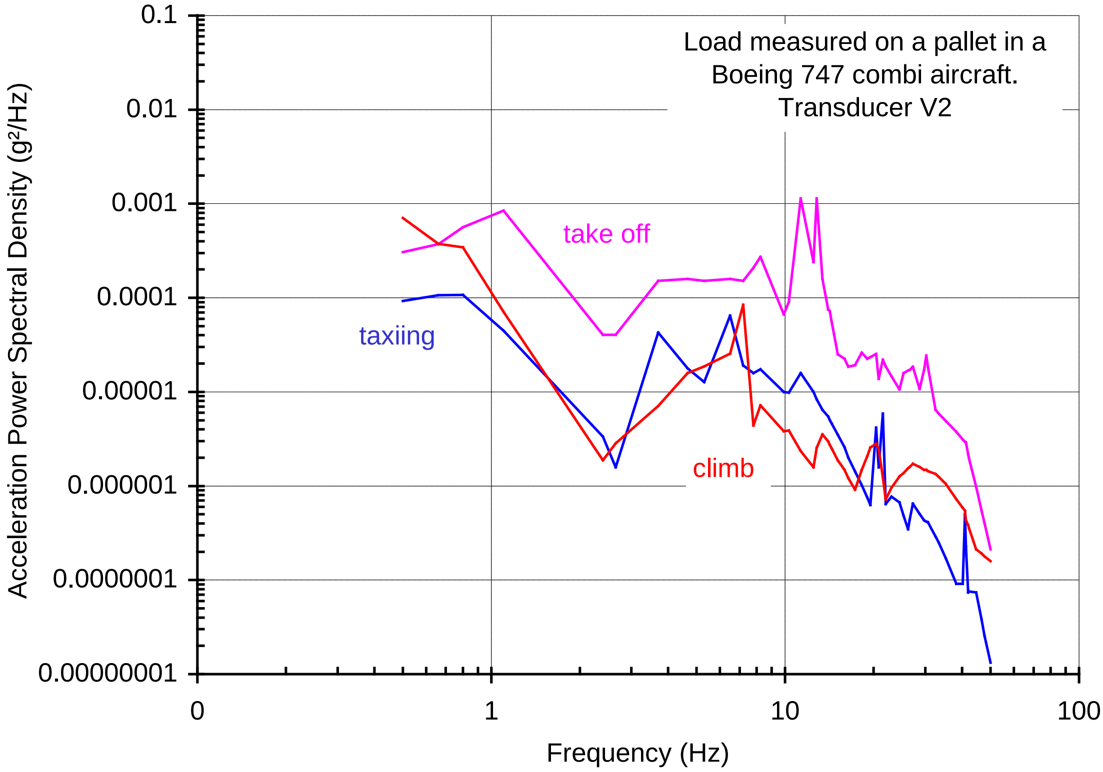

Figure 22 – Vibration measurements on a pallet in a Boeing 747 Combi aircraft (transducer V1)

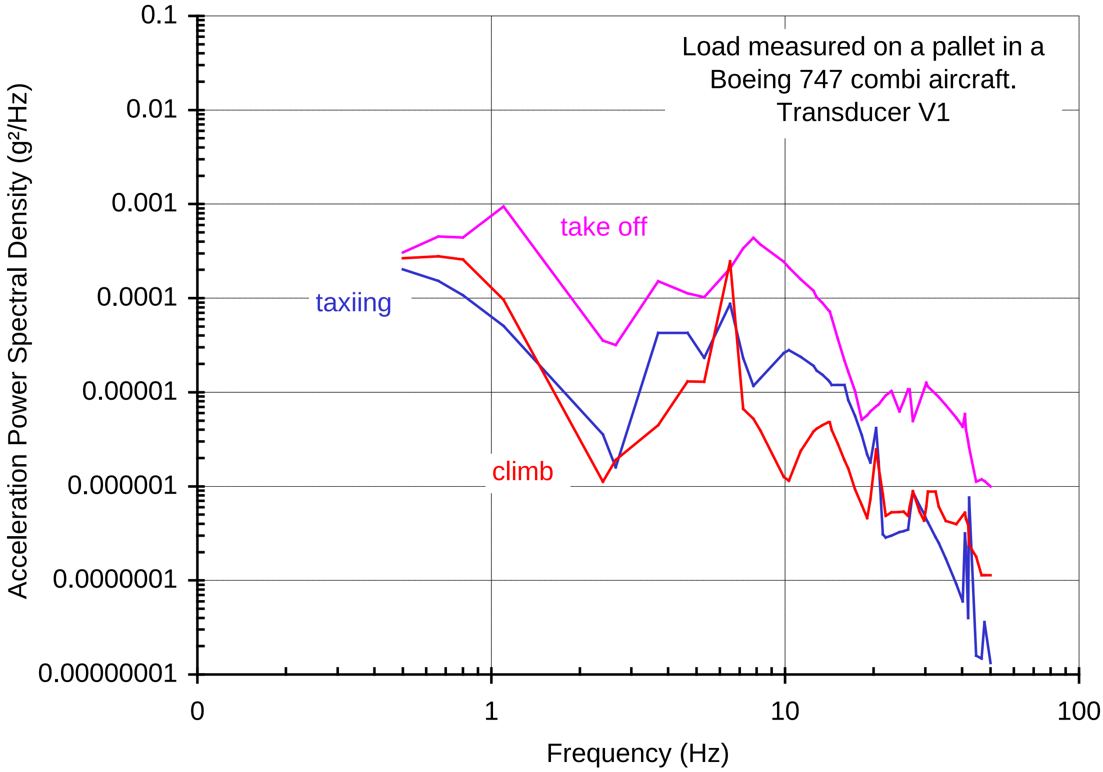

Figure 23 – Vibration measurements on a pallet in a Boeing 747 Combi aircraft (Transducer V2)

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Table 7 – Summary of DC8 air data

Phase of flight	Root mean square (g)		
	X axis	Y axis	Z axis
Taxi	0,05	0,06	0,05
Acceleration and take-off	0,09	0,19	0,18
Climb	0,09	0,17	0,11
Cruise	0,09	0,16	0,07
Decent at 1 200 m/min (4 000 ft/min)	0,07	0,12	0,09
Landing approach	0,06	0,08	0,06
Landing	0,05	0,09	0,11
Reverse thrust	0,1	0,22	0,16

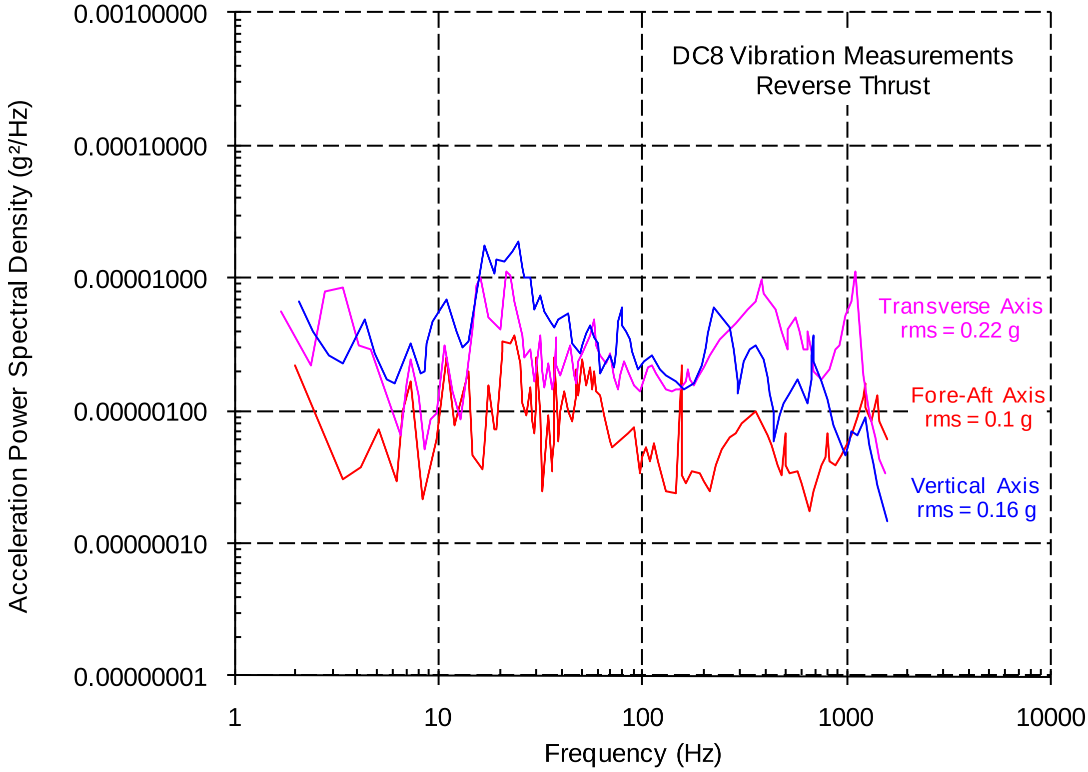

Figure 24 – DC8 vibration measurements reverse thrust

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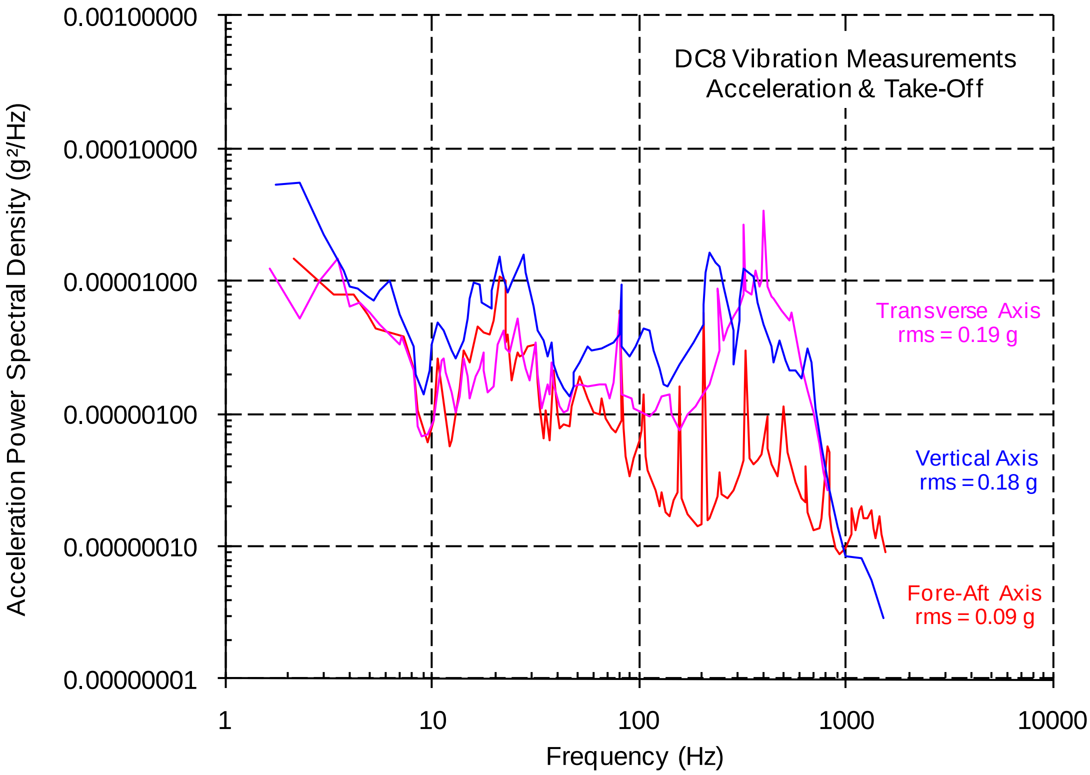

Figure 25 – DC8 vibration measurements acceleration and take-off

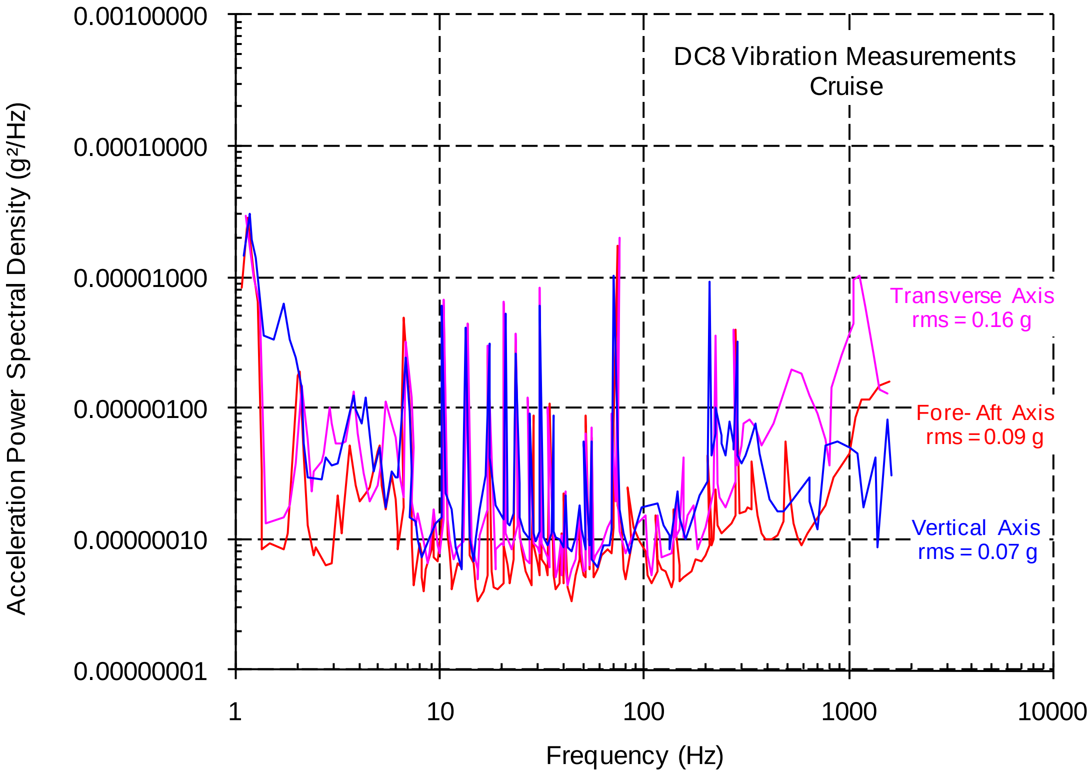

Figure 26 – DC8 vibration measurements cruise

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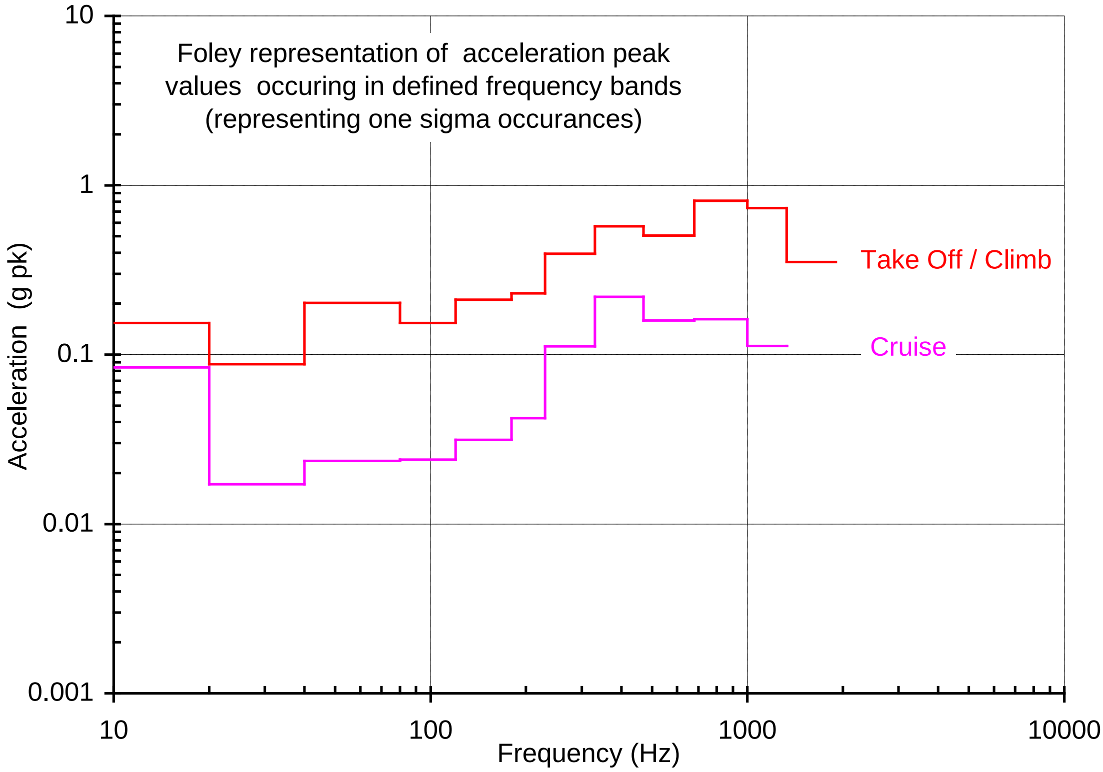

Figure 27 – Foley representation of environment for NC-135, C-141 and C-5A aircraft

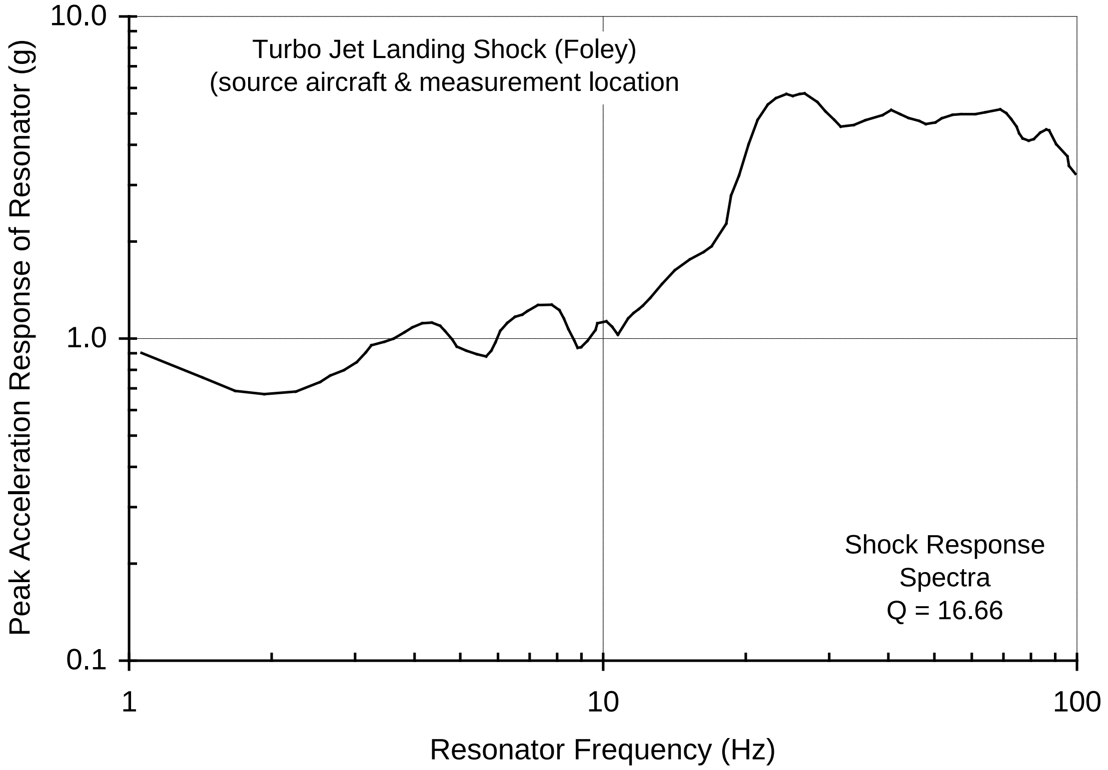

Figure 28 – Foley landing shock environment

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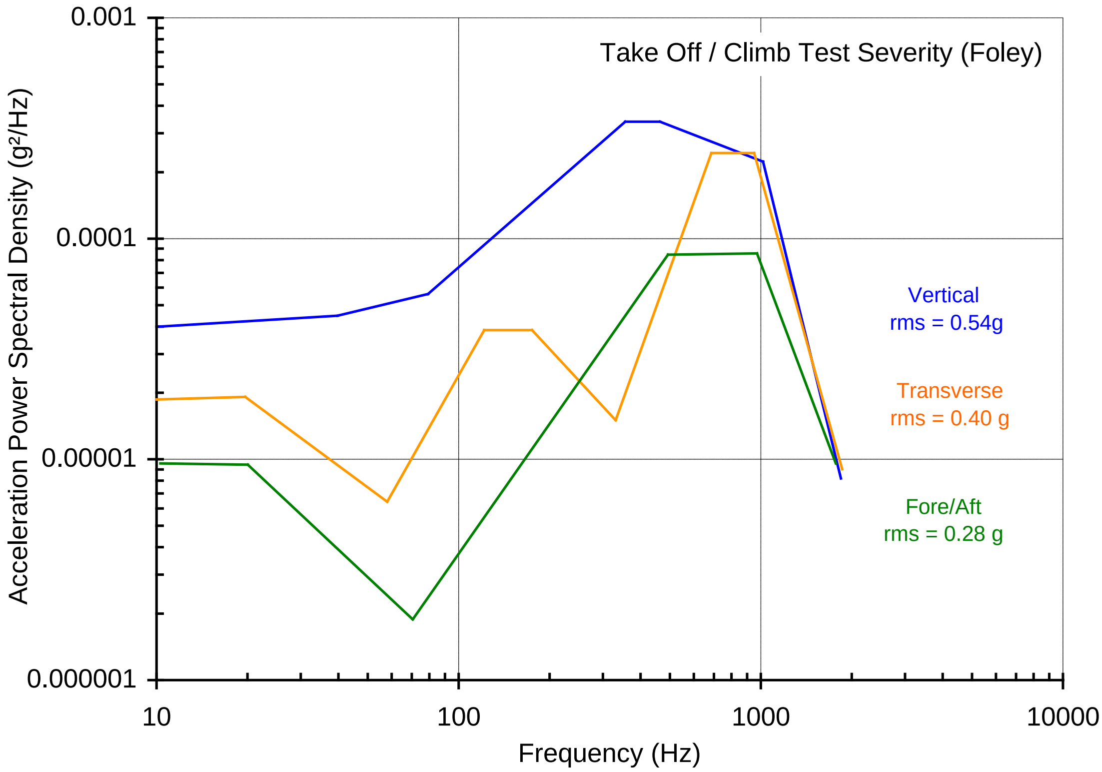

Figure 29 – Foley test severity for take-off/landing

Table 8 – Foley test severity for take-off/landing – Sine components

Frequency Hz	**Amplitude** g pk	**Applicability**
20	0,5	All axes
50	1,0	Vertical only
160	0,8	Vertical only
400	2,2	All axes
800	2,6	All axes
1 600	2,5	All axes

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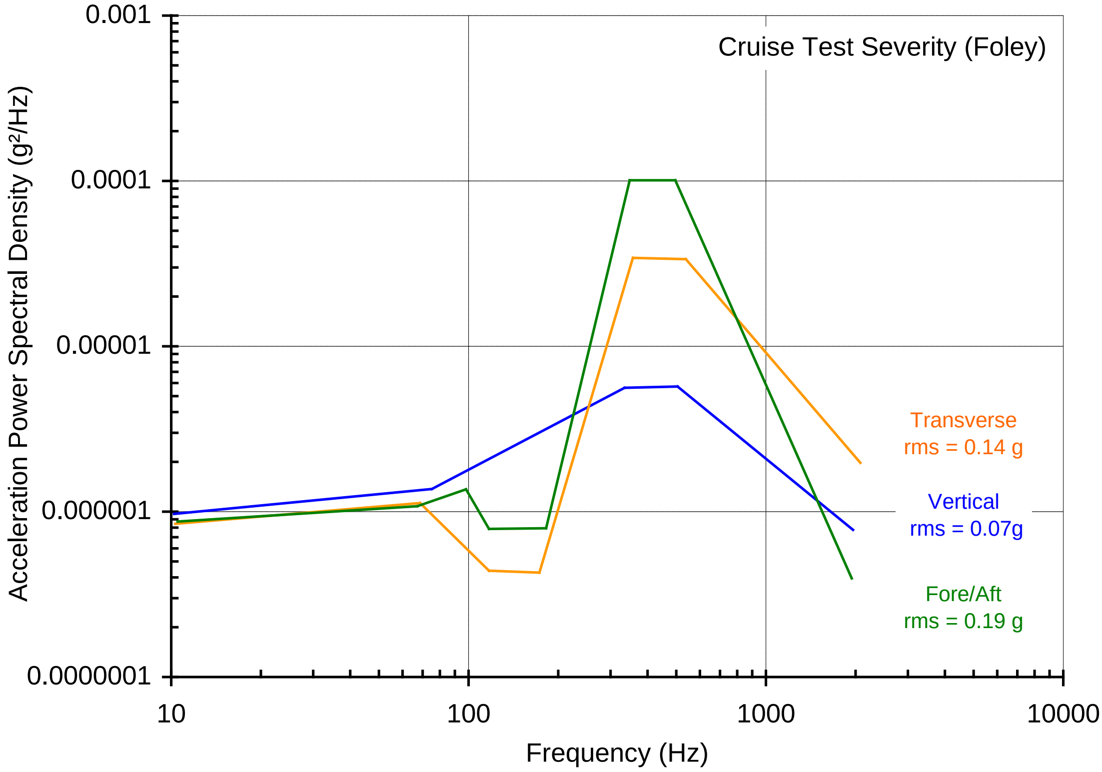

Figure 30 – Foley test severity for cruise

Table 9 – Foley test severity for cruise – Sine components

Frequency Hz	**Amplitude** g pk	**Applicability**
200	0,3	All axes
400	1,0	Fore/aft
400	0,7	Transverse
400	0,3	Vertical
800	0,5	All axes
1600	1,0	All axes

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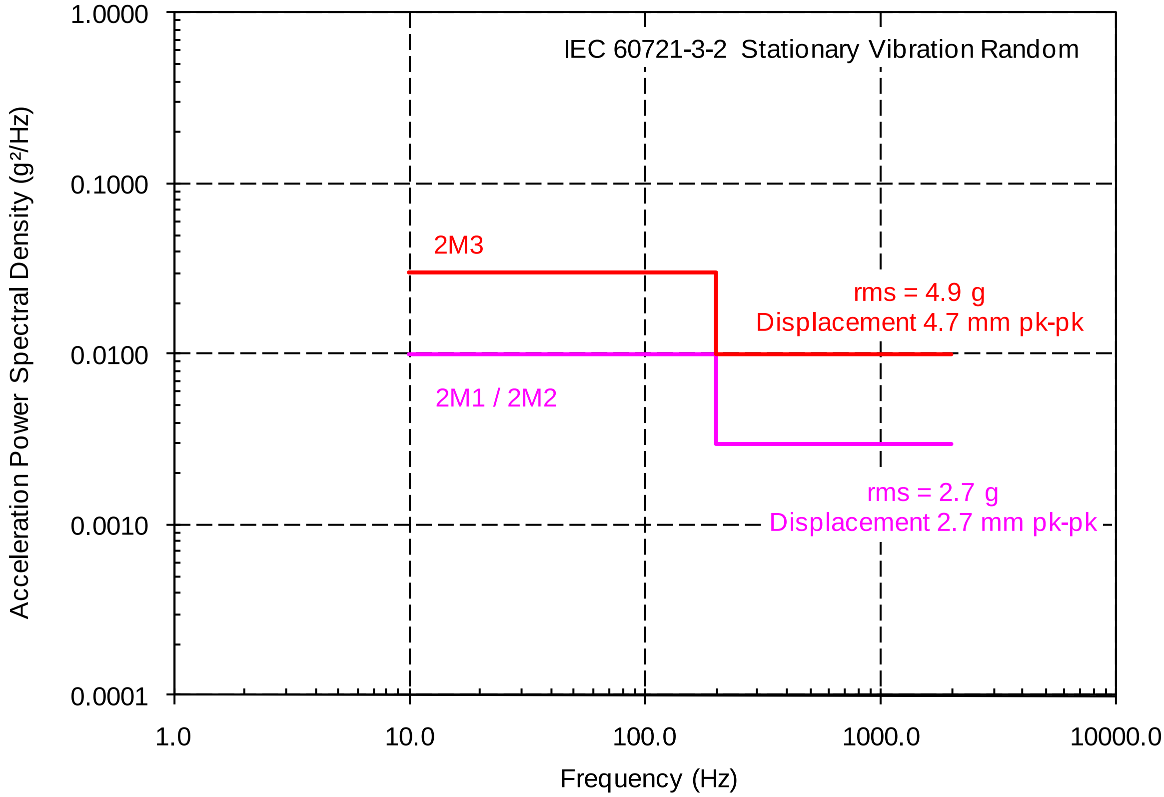

Figure 31 – IEC 60721-3-2:1997 – Stationary vibration random

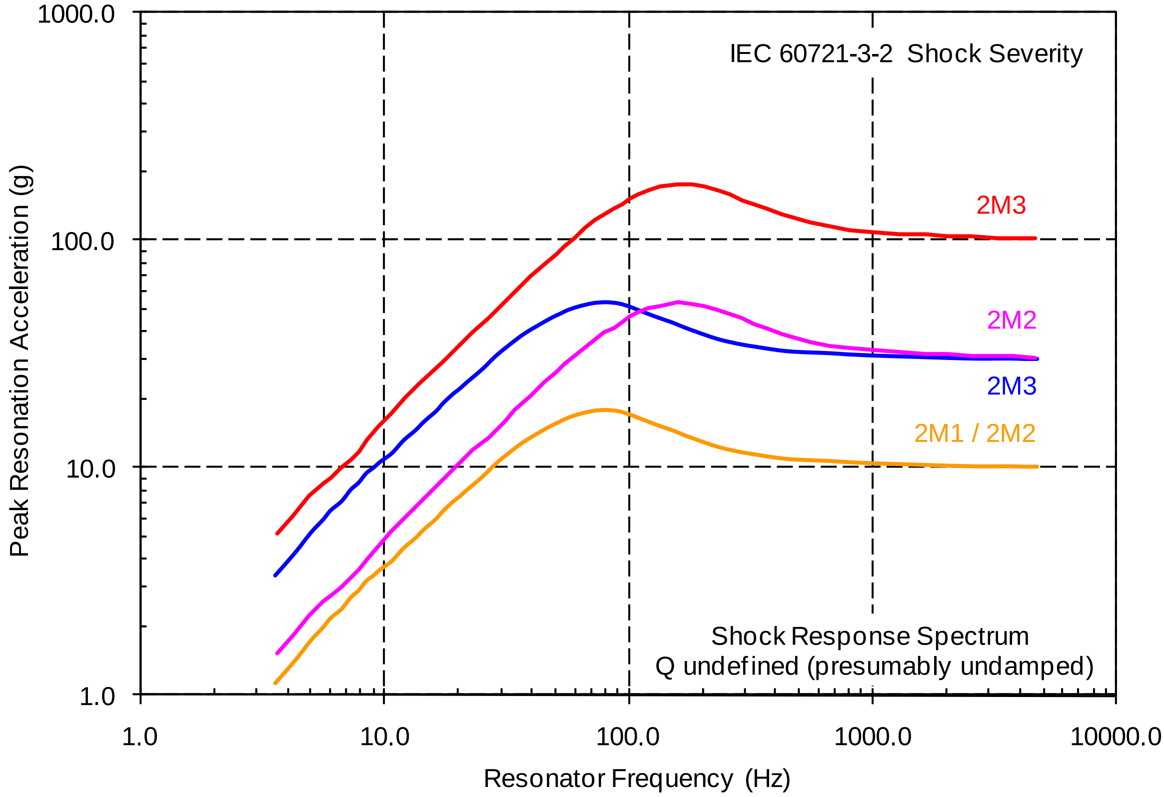

Figure 32 – IEC 60721-3-2:1997 – Non-stationary vibration including shock

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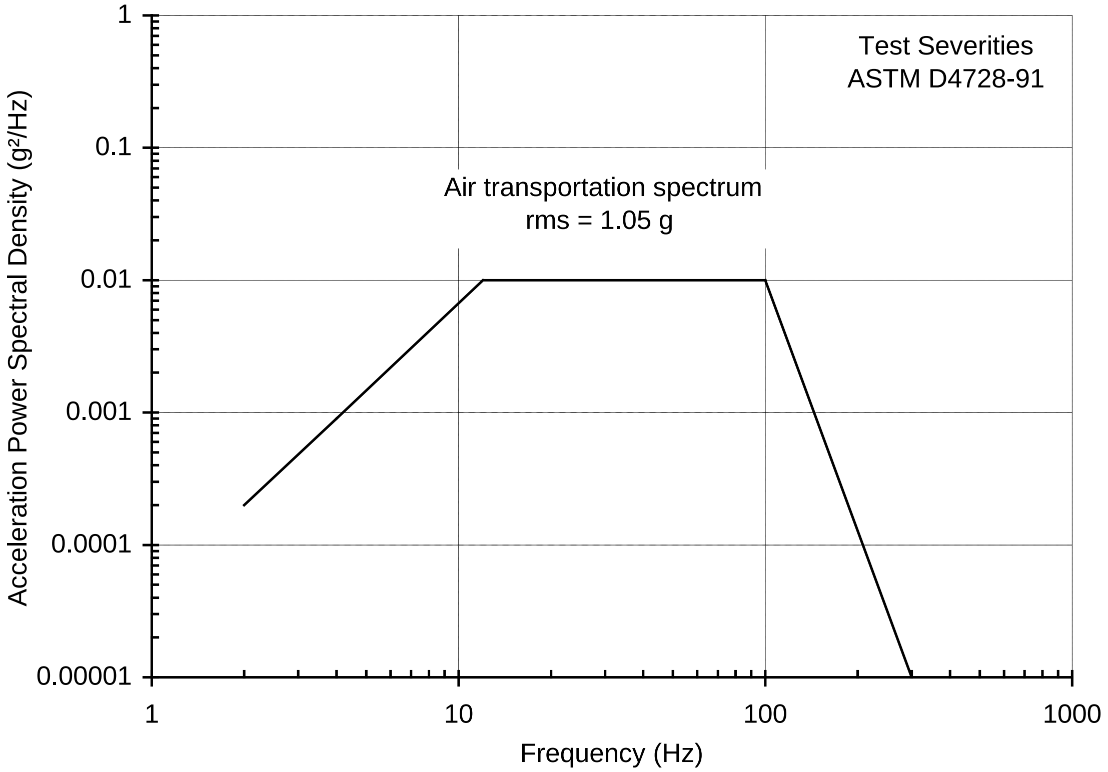

Figure 33 – Test severities – ASTM D 4728-91

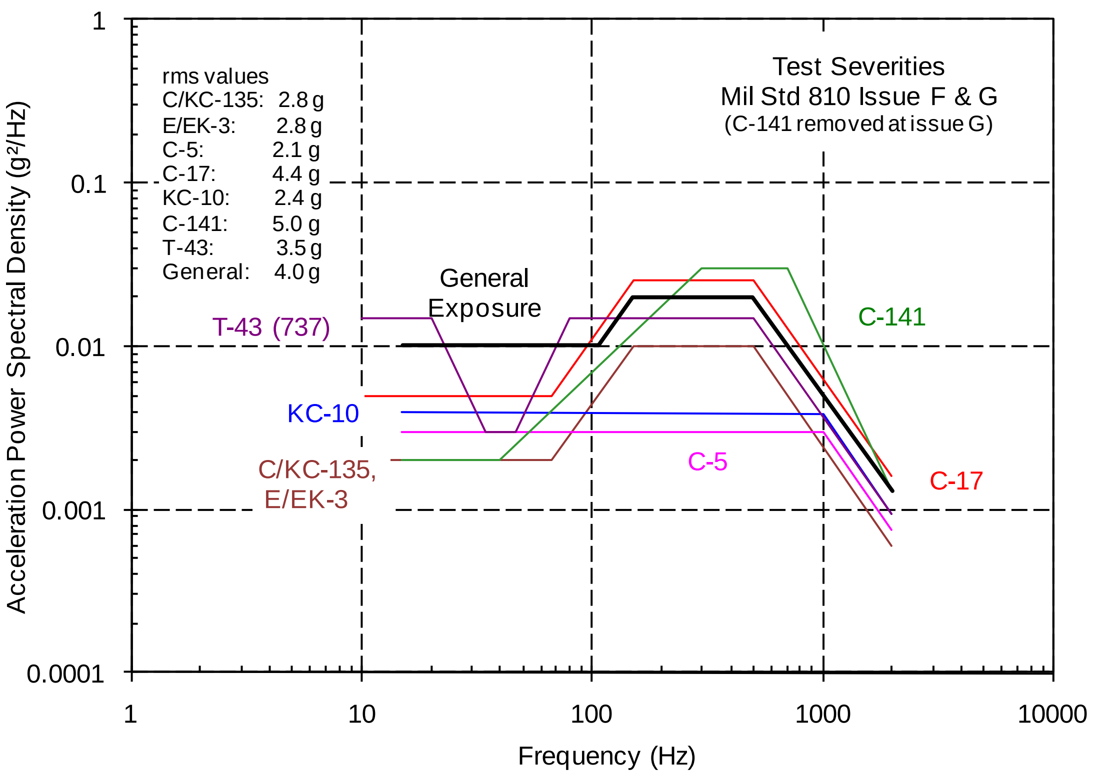

Figure 34 – Test severities – Mil Std 810 issue F and G

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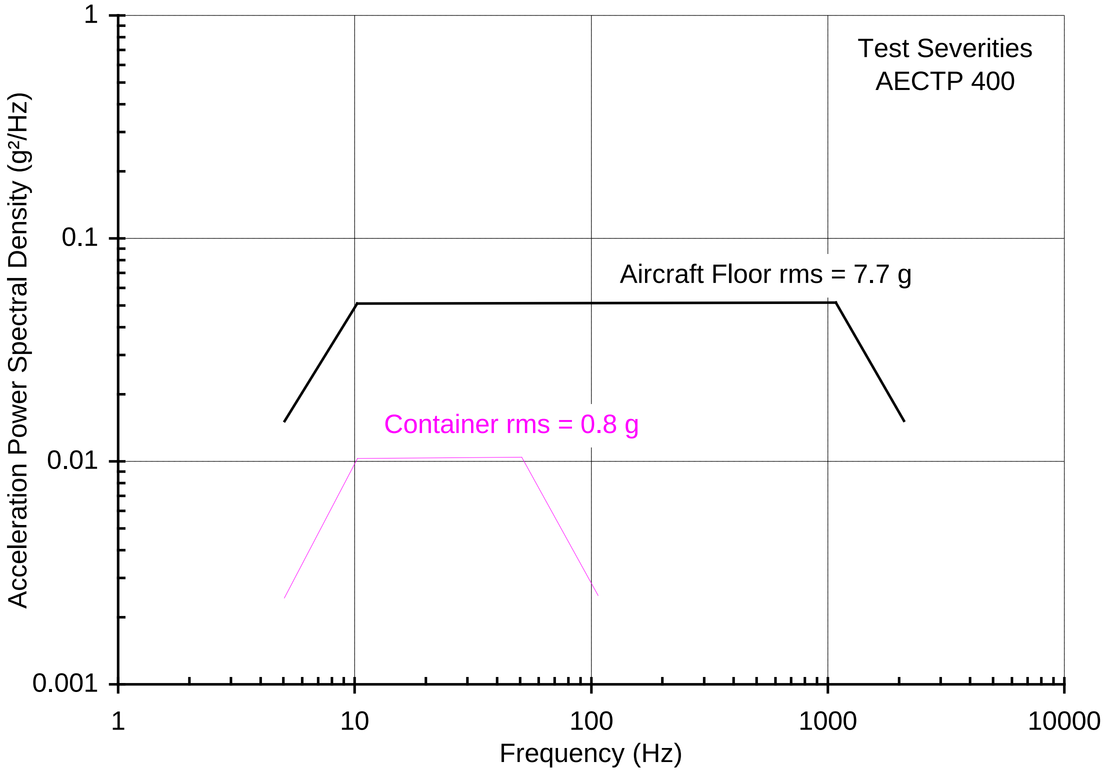

Figure 35 – Test severities – AECTP 400 (Editions 2 and 3)

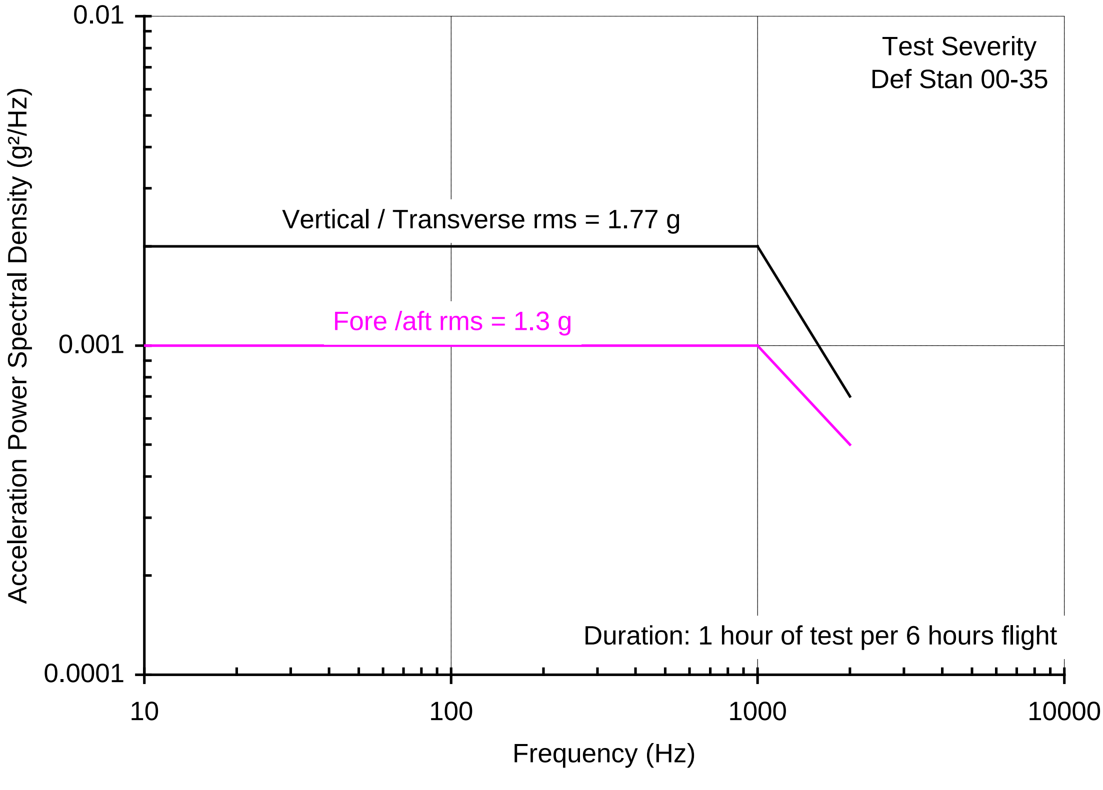

Figure 36 – Test severity – Def Stan 00-35, issues 3 and 4

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
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