A Review of Methodologies for Deriving Vibration and Shock Test Severities.

The current trend towards the tailoring of test seventies has resulted in the emergence and proposal of many new vibration test severities. As these are often derived for some quite specific conditions and applications, it is not be surprising to find that they can exhibit considerable variability. However, variability has also been observed due to the methodology used rather than variations in the original measured data. This review specifically encompasses methodologies used for the dynamic environment experienced by material carried as cargo on vehicles transported over made up roads. However, the methodologies are frequently used for other situations.

The problem is typified by a survey (Reference 1) undertaken under the auspices of the Confederation of European Environmental Engineering Societies (CEEES). This appears to confirm that no single method, for assessing road transportation vibration data, has general acceptability. Moreover, work subsequent to this survey (Reference 2) found several different possible methodologies gave acceptable results for different types of product. A further good example is found in US military standard Mil Std 810 (Reference 3), which includes transportation test seventies derived from two entirely different methodologies.

The disparity between the various methods used for deriving test severities from measured environmental data appears to arise as a result of differing opinions as to the most appropriate approach for addressing both time variant and transitory aspects of the dynamic responses. In addition variations appear to exist in how different methodologies include unquantified variables in the actual life cycle conditions. This paper specifically considers the methodologies for deriving test severities for the road transportation dynamic environment.

The Problem

A significant proportion of the dynamic environment experienced by material carried as cargo on vehicles transported over made up roads, originates from the interaction of the vehicle road wheels with the road surface. The severity of these motions are dependent upon a number of factors which include the irregularities of the road surface, vehicle geometry as well as wheel and suspension characteristics. However, one of the most significant factors appears to be vehicle velocity. Clearly during normal transportation operations the velocity of the vehicle will be varying throughout the journey, and results in time variant dynamic responses. Such responses are usually termed non-stationary.

Figure 1 illustrates typical vibration responses acquired during a forty minute journey. The figure indicates a clear relationship exists between vehicle velocity and response severity, described in terms of root mean square acceleration values derived at five second intervals. It also indicates the degree of variability of responses that occurs during a typical journey due to other effects.

In addition to variability with time, the dynamic responses also contain both continuous and transient components. Experience indicates that the transient components can be difficult to separate from the continuous, in that the transients occur at irregular intervals and exhibit a wide variation of amplitudes (References 4 to 8). Traditionally, for testing purposes, the continuous responses have been considered as vibrations, whilst the transient responses have been considered as shocks. Although these groupings are convenient for establishing test requirements, in reality the separation of the continuous and transient components is often quite arbitrary and, almost always, difficult to quantify. Clearly, the use of an inappropriate method for separating continuous and transient dynamic responses may particularly influence the vibration test severity.

Due to the difficulties of establishing 'worst case' road conditions, use is sometimes made of standard test tracks. The use of such tracks may have advantage in certain circumstances, as they permit standard road surfaces to be traversed at constant speed, hence significantly reducing the non-stationary component of the dynamic responses. Test tracks may also reduce the occurrence of transients within the responses, although, this may not always be the case.

For smaller payloads the major dynamic responses may arise from the payload 'bouncing' on the cargo deck of the vehicle or jostling' with other cargo. Whilst, such effects are not specifically considered by the remainder of the paper, the separation of these so called "loose cargo" effects from those arising more directly from the carriage vehicle is yet another problem facing the environmental engineer.

The Differing Test Generation Approaches

A number of approaches are in current use to derive vibration test seventies from measured data. A number of methods are described here and the advantages and disadvantages of each discussed. However, the different approaches considered are far from an exhaustive list and, even of those considered, a number of derivatives are known to exist. The actual methods selected, for discussion here, are those which appear in a number of current or proposed national standard test requirements.

The example of use of each method is based upon measurements in a transport aircraft. Figure 2 indicates the time history of a measurement made on the floor of the aircraft during a flight of around 100 minutes. The measurement is in the aircraft vertical axis and is roughly in the centre of the cargo bay floor. During the flight the aircraft flew at a variety of airspeeds and undertook a number of manoeuvres. The measurements start just before take off and terminate just after landing. As can be clearly seen vibration measurements vary considerably. An Amplitude Probability Density (APD) and a Power Spectral Density (PSD) , both computed from the entire flight, are shown in Figures 3 and 4. The PSD represents the mean values for the entire flight.

Conventional PSD Enveloping Approach

This is probably the most common, oldest and simplest method in current use to derive test severities which are invariably in the form of Power Spectral Density (PSD). Although in use before the advent of digital analysis equipment, the availability of such equipment has meant this method is readily viable for essentially every analyst.

Process. The derived vibration test seventies are based upon PSD measurements from different measurement locations and conditions. Essentially Power Spectral Density spectra are computed from all these measurements. These are then overlaid and a spectra formed by creating an envelope over the top of the overlays of the PSD values. Whilst, this enveloping spectra is often derived by judgement, more quantitative approaches such as enveloping over one third octave bands may be adopted. The envelope spectra may used directly as the test spectra, but it is more commonly factored to encompass possible unquantified variabilities in actual life cycle conditions. Additionally it is also usual to further envelope the actual PSD values to produce a spectra with fewer defining points to simplify the definition of a test severity. Frequently any factoring applied on top of the enveloping spectra is a simple multiplier. Typical factor are 3dB or 6dB on either spectral amplitude or rms value depending upon quality of data and / or level of confidence required. In recent times the use of more specifically derived factors has become more common. The derivation of such factors is intended to take into account credible variations in the excitation mechanisms as well as build and method of operation of the platform.

Example of Use of Method. Figure 5 shows overlaid PSD measurements for 40 different selected events mostly occurring during the flight but include a few measurements made on the ground. In this case the PSD from a single event produces the largest spectral amplitudes over almost the entire frequency range. However, this is not always the case. Shown in Figure 6 is a credible envelope of the highest values. In this case the envelope spectra can be fairly simplistic without incurring large variations between the envelope and the actual largest spectra. Again, this is not always the case and in some cases quite complicated envelope spectra may be needed to ensure a reasonable large variation between the envelope and the actual largest spectra.

Assumptions / Limitations. The main body of limitations to this approach are essentially the limitations in the use of the PSD as a data reduction procedure. Specifically the temporal averaging process inherent in the computation of a PSD, implies that the PSD it has no real ability to accurately describe time variant data. Moreover, it does not allow the effect of transient responses to be separated from the continuous responses. This can be a problem particularly for wheeled vehicle data were transients may be embedded within the vibrations. For the approach to produce meaningful results, some control over the data gathering must be imposed. This is traditionally achieved by selecting specific periods of constant (stationary) vibration conditions for analysis. This can be difficult when real world or covertly acquired measurements are used. The availability of recording equipment able to allow long periods of measurement or solid state recorders which record only the highest amplitude blocks of vibration are both useful. In the example been used throughout this report, individual flight conditions have been identified which produce different spectra. These are shown in Figures 7 to 10, which are envelopes of all vertical measurement locations on the cargo bay floor. For each of these groups of events separate enveloping test spectra could be developed. The advantage, in this case, would be to separate the events that occur only one in a flight from those occurring for the majority of the flight.

Advantages / Disadvantages. The approach, has the advantage, that it represents the most convenient data analysis method available and produces an environment measurement from which vibration test seventies can be easily derived. Provided care is taken in the process the method usually provides a test which takes into account the most severe amplitude cases. The main disadvantage is that the largest spectral amplitudes may only occur for a very small percentage of the duration actual usage. As a consequence the test may induce unrealistic damage if applied for unreasonable periods. A related disadvantage is that the enveloping process inherently increases amplitudes across the frequency range by various amounts depending on well the spectral envelope represents actual conditions.

Repeatability. Good statistical accuracy can achieved for each individual spectra by use of a record of sufficiently duration. However, the enveloping does not usually improve the statistical accuracy as frequently a few spectra supplant all others. It is not uncommon for the envelope to be actually based on a spectra computed from only a few seconds of data out of a several hours of measurement. Another limitation on repeatability occurs when the shape of the various spectra differ. This can occur as a consequence of changes in platform, excitation mechanism (road surface) or because measurements from different locations are been included. As a consequence the resultant enveloping spectra may not represent a number of condition that can realistically occur simultaneously or for that matter are physically realisable.

Applicability. The approach is applicable when the data are stationary. To achieve this practically the vehicle under investigation must be traversing test tracks at constant speed or specific periods of constant vibration are selected.

Traceability. The PSD generated by this approach is statistically sound provided that the “rule” of stationarity is followed. If non-stationary data is used, the outcome still has a statistical basis but not that arising from the entire record.

Uncertainty Factors. In any measurement exercise a number of unquantified factors are likely to exist. Such factors can include the effects of different vehicles, road surface and quality of the driver. With this method the envelope drawn over the actual measurements is increased in amplitude to account for an estimate of the unquantified factors. The estimate may be based upon previous knowledge or experience. Care needs to be taken when simplifying the resultant “envelope” to ensure that unrealistic factors are not unintentionally introduced.

Relationship with Other Methods. A fair number of other methods are based upon the PSD enveloping approach and are intended to rectify various limitations of the basic method.

The Peak Hold Spectra Approach

A derivative of the PSD enveloping method that is sometimes adopted is to utilise "peak hold" values. This removes some of the variabilities of the previous approach and it allows the upper limit effects of the non-stationary effects to be evaluated. Peak hold spectral density values may be used alone, that is, instead of the conventional (average) PSD. However, the peak hold spectra can also be usefully used to augment the conventional PSD enveloping approach. Used in this way the worst case effects of the environment can be established.

Process. In this context the "peak hold" values are essentially the largest PSD values that occur, in each, spectral band, over the analysis record length. Although the measured data can be handled in the same way as the previous methods, the need to process over essentially stationary events is not necessary. As a consequence a more “automated” analysis approach can be taken, requiring less expertise to perform. As was the case in the previous method the peak hold is treated as the “envelope” of the actual measurements. However, in this case converting this envelope to a PSD test spectra requires a PSD which gives the same peak hold values. Typically this would involve reducing the spectral values equally across the entire test frequency range to produce a root mean square value of one third the rms computed from the peak hold spectra (as random vibration tests normally limit crest factor to 3).

Example of Use of Method. Figure 11 shows the peak hold spectra computed for 40 different selected events mostly occurring during the flight but include a few measurements made on the ground. In this case the spectra from three events contribute to the enveloping peak hold spectra. Shown in Figure 12 is an envelope of the peak hold spectra and a PSD test spectra which would give the same peak hold spectra. This assumes a gaussian random test with a crest factor limited to 3. In such a case the test spectra would be 9.5 dB less than the enveloping peak hold spectra. However, a simplification assumption of 10 dB is not unreasonable. For information the peak hold spectra from the entire flight is shown in Figure 13. In this case the spectra is not significantly different from the peak hold computed from the individual events (indicating the events encompass the worst case).

Assumptions / Limitations. The use of the combined peak hold values and conventional PSD data can give a useful indication of the spread between peak and mean spectral values For transportation data, the spread between the conventional PSD values (i.e. the mean values) and the peak hold values may be quite considerable. Of course, a conventional Gaussian random signal will exhibit a variation between its peak and mean spectral values, whilst a further variation will occur if the data contains any time variance (i.e. non-stationary) effects or embedded transients.

Advantages / Disadvantages. The main advantage of the use of the peak hold spectra is that it ensures the absolute worst case of the measurements are encompassed. As different parts of the worst case spectra may arise from several different events, the resultant test seventy is almost certain to be a conservative test level. In those cases the spectra are almost certain to represent a condition which would have a very low probability of occurrence. Whilst, this may be particularly important for exercising certain types of failure mode, it can if applied for unreasonable durations give rise to unrealistic failures. is particularly germane when the data contains non-stationary and transitory conditions. When used in conjunction with the conventional mean PSD approach, the peak hold spectra can be a useful indicator of the effects of non-stationary and transient conditions. The peak hold spectra can also allow the margin between the test severity and the absolute worst case conditions to be quantified. The ratio between average PSD and peak hold is also sometimes used as a crude indicator of the presence of periodic components (from engine, drive train etc).

Repeatability. No real statistical confidence can be placed in the peak hold spectral values. The resultant peak hold spectra may comprise a very low probability occurrence of the original waveform appearing for only a transitory periods. As such repeatability and confidence can be extremely poor.

Applicability. The peak hold spectra may represent a combination of a number of condition that can not realistically occur simultaneously or for that matter be physically realisable. Also the peak hold spectra is not a PSD and should not be applied directly as vibration test severity. To do so would incorrectly implement the peak hold spectra as a conventional PSD, effectively incorporating a huge factor for test conservatism. The usual method of implementation is to derive a PSD would produce, in the test, a similar peak hold spectra.

Traceability. As the peak hold spectra is statistically poor the verification of the result is likely to be similarly so. Additionally as the final peak hold spectra is likely to originate from a number of different events, the identification and verification of specific conditions creating any worst case is problematic.

Uncertainty Factors. With the PSD enveloping method the envelope drawn over the actual measurements is increased in amplitude to account for an estimate of the unquantified factors. The peak hold spectra allows the user to establish a upper condition from the measurements by which to support previous knowledge or experience. The use of peak hold also any unrealistic factors introduced in the spectra simplification to a test spectra.

Relationship with Other Methods. A better statistical description of worst case conditions can be established from the Amplitude Probability Density approach described hereinafter. The Maximum Response Spectra also allows consideration of the effects of worst case conditions. With that said compiling Peak Hold Spectra requires very little effort beyond a conventional PSD. As such the approach can be a useful first indicator as to whether further consideration of worst case conditions is necessary.

The Foley or SANDIA Approach

The road transportation test severities presented in Mil Std 810D for "composite" wheeled vehicles are based upon a set of environments descriptions, derived in the early 1970's by Foley from the US Sandia National Laboratories at Albuquerque (Reference 10). The process adopted by Foley is somewhat different to that used elsewhere and consequently deserves consideration here.

Process. The road transportation environmental descriptions are based upon measured data acquired during actual road transportation. These data represent a wide variety of vehicles, loading configurations, locations and speeds. The vehicles were all US types with both pneumatic and spring suspensions. For a specific vehicle / location the root mean square values in each of several frequency bands (of different bandwidth) were measured. The most severe value for the different vehicles and locations, in each band, are those used as the environmental description. In general, only the most severe 10% of any record was utilised in this process. The creation of a vibration test severity appears to involve converting the rms values of the environmental description to "equivalent" Power Spectral Density values and then forming an envelope over these values. This latter process is neither fully documented or particularly well defined and seems to include a fair degree of judgement.

Example of Use of Method. The Foley method is quite difficult to reproduce as it requires an intrinsically different data analysis approach to those used elsewhere. It also requires a fair degree of judgement to set up the different frequency bands and pre-data selection. For these reasons undertaking an example of the method is not particularly helpful.

Assumptions / Limitations. The SANDIA approach is in part intended to address the problems associated with non-stationary effects, transient conditions as well as the variation in dynamic characteristics between different vehicles and locations. The method intrinsically assumes a broadly similar spectra between vehicles and locations. However, the variations that do occur are accommodated by the relatively broad bandwidths adopted. Taking only the 10% of the data with the largest amplitude ensures the worst cases are given weighting. However, the result is both a temporal and spectral average of the 10% of the data considered. The method does not address the variabilities in a manner which allows them to be quantified. Moreover, when including different vehicles and location the result is particularly sensitive to the selection of the different analysis bandwidths, and in the conversion of the environmental description to a test severity.

Advantages / Disadvantages. The SANDIA analysis approach can be undertaken with relatively simple equipment (filters and true rms meters) and is tolerant of variations between vehicle characteristics (as a consequence of the use of rms values along with a large analysis bandwidth). Moreover, unlike some other approaches, the method acknowledges the problems associated with non-stationary and transients conditions. Unfortunately it tolerates these effects largely by creating bandwidths broad enough to be insensitive to these variations. As a consequence, the method can produce test levels markedly lower than most other methods.

Repeatability. As the Foley approach does not produce an output that can be used directly as a vibration test specifications it has to be converted in to a PSD. The conversion process that Foley used was not well documented. Attempts to “reverse engineer” his conversion suggests that it was not based upon a quantitative method. It seems to have included a test margin but it does not seem to be consistent across the full frequency range.

Applicability. The approach is useful when vehicles of similar (but not identical) characteristics need to be addressed.

Traceability. The process does not readily facilitate data verification as many of the data characteristics are lost. Moreover, the methodology requires pre-selection of bandwidths, should these be inappropriate (i.e. if the vehicle dynamic characteristics differ from those assumed) nothing can be done to correct the situation. As a consequence the result can be unduly influenced by limited or anomalous portions of the data. This can be a particular concern when using real road data as the worst conditions may be generated by a very limited range of occurrence and specific vehicles. As a consequence it is almost impossible to verify the Foley road vehicle severities with current day vehicles.

Uncertainty Factors. The conversion from rms values to "equivalent" Power Spectral Density values seems to be the main opportunity to include factors for unquantified variables. The main limitations here are that the existing methodology does not seem to be based upon a quantifiable process. As such the user is unable to quantify the factors already included in the analysis. The other uncertainty is related to the selection of worst case conditions.

Relationship with Other Methods. The method differs significantly from other commonly used approaches. The method can be used with only simple equipment. Nevertheless, today such equipment is likely to be more expensive to utilise than more sophisticated computer based systems. Also the method seems to produce test amplitudes lower than most others and with a relatively simplistic spectral shape.

The Aberdeen Proving Ground Approach

A relatively more recent introduced vehicle transportation test seventies presented in Mil Std 8I0D were derived using a procedure significantly different from the preceding method. This alternative approach was developed, in the late 1980's, specifically to derive Mil Std 810D test severities for wheeled and tracked vehicles. The method was developed by the US Army Aberdeen Proving Ground, using there test track surfaces, and has largely been automated. The method has been utilised for other applications but not always particularly successfully.

Process. This method uses the measured acceleration Power Spectral Density values which for consistency must be calculated using a common bandwidth (1 Hz was used by Aberdeen). As well as computing the usual mean value the standard deviation of the variation in each band is also computed. The measured data are acquired from a selected range of vehicle locations, test track surfaces and speeds. A vibration spectra for each individual measurement condition is computed as the mean plus one standard deviation value, in each of frequency band. The spectra for surfaces and speed are combined by computing the mean plus one standard deviation spectra of the individual measurement conditions. These are further combined for each location within the vehicle again by computing the mean plus one standard deviation value of the previously combined values. When several vehicles are to be considered, the computation of mean plus one standard deviation is repeated yet again. The test spectra is derived by enveloping the final description.

Example of Use of Method. Figure 13 shows the PSD statistics for the full flight. One of these is the mean plus one standard deviation values. All the values shown in Figure 13 can relatively easily be computed whilst generating a conventional PSD (which is shown as the mean spectra). Figure 14 shows the various mean plus one standard deviation plots computed from 40 different selected events mostly occurring during the flight but include a few measurements made on the ground. These 40 separate spectra can be combined by computing the mean plus one standard deviation spectra of the 40 individual event spectra. This combined spectra is shown in Figure 15 which is for all events but at a single location. Figure 16 is obtained by repeating the process again for all vertical measurement cargo bay locations. It is worthy of note that the spectral values of the mean plus one standard deviation spectra computed from the entire flight (Shown in Figure 13) are about one quarter those computed from the 40 separate events (Figure 15). This is because the periods at low level periods are excluded by selecting the events.

Assumptions / Limitations. In some ways the method can be considered as an enhancement of the peak hold approach. However, unlike that method, statistical confidence exists in the two values computed (the mean and variance). Unfortunately, like the peak hold method, the results from the Aberdeen Proving Ground approach can easily be distorted if non-stationary data are included. For this reason the procedure dictates the use of specific test tracks traversed at specified constant speed. The use of relatively narrow bandwidth means that the method is not very tolerant of variations in response spectra content between vehicles and locations. The consequence of this is that the more locations and vehicles included in the data ensemble, the more likely are the spectral peaks to be "averaged out". For this reason a degree of selectivity is usually necessary (and exercised) over the incorporation of data into such an ensemble. For the example used throughout this report, the variations between events and between locations are far from a gaussian distribution. The distribution of amplitudes across events in particular is significantly skewed. When only a small percentage of events give the highest levels, as is the case here, a danger exists that the derived test severity does not encompass the worst cases. At least one documented use of this method indicates this has occurred.

Advantages / Disadvantages. An important advantage of the method is that it can be relatively easily automated on a digital computer analysis system. Moreover, the method readily permits the inclusion of a quantifiable and consistent degree of test conservatism. Unfortunately, because it necessitates the use of specific test surfaces and vehicle speeds, the method is not particularly suitable for data acquired on normal road conditions. Few attempts to use the method with real field data are documented and some of those do not seem to be particularly satisfactory. The inclusion of a wide range of life cycle conditions can mean that the test severity is significantly lower than the worst case. Even the repeated use of mean plus one standard deviation may not result in test levels which encompass the worst case conditions. The method does not intrinsically check for this but it is strongly recommended that a user does so.

Repeatability. The method is partly able to quantify the variations that occur during the measurements. Four groups of variation are encompassed viz. those due to random measurements, road surfaces, locations within a vehicle and different vehicles. The process is effectively including four factors or margins to account for variability. The first margin (of one standard deviation) is on the normal random measurement error. The margin will be minimised by a sufficiently long measurement record provided the data are stationary. If the data are time variant the margin will be influenced by the amount of non-stationarity. The variation due to non-stationarity will be greater with this method than for a normal PSD approach. The second margin is for road surface/ speed and is usually controlled by using designated test tracks at the US Army Aberdeen Proving Ground. The effect of using other surfaces is unknown but it must be assumed that significant differences could occur. The third factor is locations within the vehicle and is controlled by using only generic locations designated by the US Army Aberdeen Proving Ground. The effect of using other locations again must be assumed to be significant. The fourth factor is due to different vehicles is also controlled by judicious selection by the US Army Aberdeen Proving Ground. Without this level of control by the US Army Aberdeen Proving Ground little repeatability could be expected.

Applicability. The US Army Aberdeen Proving Ground approach makes some effort to quantify the effects of 4 significant variations that influence the vibration conditions induced by vehicles. However, whether this can be achievable by a common factor and a semi “automated” process is questionable. The basis for using a the mean plus one standard deviation seems no more than convenience as it appears to have no firm technical or statistical basis. The method has been used for environments other than vehicles but with only limited success. The main difficulty is the necessary control over the measurement conditions.

Traceability. Once the process is completed (for a particular vehicle) it is not possible to trace any individual variations due to surface or location. Nor is it possible to derive the original conditions producing the resultant severities. This inherent inability to verify the quality of data (or more specifically the tracability of rogue data) is compensated for by the use of a rigorous verification process during data acquisition and processing. Aberdeen have published widely the basis for this process which is essentially a fully automated.

Uncertainty Factors. As already indicated the process attempts to form some repeatable basis including factors to account for variations in location, surface and vehicle. However, this assumes an essentially gaussian variation or at least a symmetric distribution. Moreover, the method begs the question as to whether the repeated use of mean plus one standard deviation is sufficient factor. Experience with actual field data would suggest such an assumption is not a priori.

Relationship with Other Methods. As illustrated by Figure 13 the method can, with little extra effort, be used along side that of a conventional PSD method or even the peak hold method. The methods has limited similarity with an approach published by NASA (Reference 12). This uses a factored standard deviation to create a test spectra for rocket launch / flight from an ensemble of separate flight measurements. The NASA approach is specifically intended to allow information from only a few launches to create a test severity which will, with a high degree of confidence, encompass likely worst case conditions. The factored standard deviation is based upon a Student T distribution which related small sample size and required degree of confidence.

The APD Approach

A method, used by the Cranfield University and proposed for inclusion in UK Def Stan 00-35, utilises both acceleration PSD values and amplitude probability densities (APD). The PSD is utilised to give the spectral shape to the test severity but the overall amplitude is modified to allow the measured probabilities densities to be encompassed. This can be achieved, in practice, by several strategies but the simplest involves using several levels of vibration amplitude, each used for a different test duration.

Process. The general principles behind this procedure are described in Reference 9. Essentially, for all the data for a particular transducer, both the Amplitude Probability Density and the PSD are computed. Several gaussian distributions are summed to match the APD. The PSD is used to establish test spectra in same manner as described for the conventional PSD approach. The overall amplitude is then adjusted based upon the Amplitude Probability Density, which also gives the test duration. Alternatively the APD can be used to determine the split between vibration and shock testing. The amplitude distribution will then give the duration of the vibration and relative number of shocks required.

Example of Use of Method. Shown in Figure 17 is the APD for the full flight (also shown in Figure 3). Superimposed upon that APD are five gaussian distributions each limited to a crest factor of 3. That crest factor is that commonly adopted when undertaking random vibration tests. The five gaussian distributions have been fitted to the overall APD by adjustment of the relative probability (related to the test duration) and the rms of the vibration. The test spectra used is that developed separately but with the overall amplitude adjusted according to the APD fits. These are shown in Figure 18. In this example it is likely that the lowest level vibrations would be incorporated into the next highest severity by appropriate factoring using Miner-Palmgren.

Assumptions / Limitations. The method assumes that the spectral content of the dynamic responses remains similar at all amplitude levels. Current measurements from road vehicles indicate this assumption is generally valid, although its verification for other vehicle type would be required. In the example used throughout this report the spectra for high amplitude short duration events differ from the longer duration straight and level flight conditions. By including low occurrence events the method can also allow the effects of transients events to be quantified not only in terms of amplitude but also in terms of relative rates of occurrence. In such cases the transient events can be replicated by means of a period of short duration high amplitude random vibration or a shock test programme. In the real environment both continuous and transient responses occur concurrently, mostly, current vibration test equipment necessitate the different test amplitudes to being applied separately. This method permits the separation of the two tests in a quantitative manner.

Advantages / Disadvantages. The approach has the advantage that it allows both non-stationary and transient data to be accommodated. The APD's together with the associated PSD's can be used directly to create a good environmental description for a particular vehicle. In particular it allows test durations to be established on a sound technical basis. The main disadvantages are that the method assumes that the spectral content of the dynamic responses remains similar at all amplitude levels. It also requires very long duration measurements to obtain good confidence in the APD values at low occurrence rates.

Repeatability. An APD alone cannot intrinsically differentiate between a non-gaussian process and a non-stationary one (Reference 10). As the method set out here assumes that the measurements are non-stationary then intrinsically a gaussian distribution has to be assumed. This may need to be verified by a separate method. Typically vehicle suspension non-linearities may distort the distribution. To quantify, with statistical accuracy, the high amplitude / low occurrence events with a reasonable degree of confidence, a very long measurement record is required.

Applicability. The approach is usable with measurements containing both non-stationary and transient data. The approach also alleviates the need to undertake separate "vibration" and "shock" analysis (and testing). However, probably the most notable aspect of the method is that it expands the concept of "tailoring" vibration test seventies beyond those of using power spectral density based measurements alone.

Traceability. The APD generated by this approach is statistically sound and frequently comprises a useful data validity check. As already indicated the APD can be misinterpreted when the data are non-gaussian and non-stationary.

Uncertainty Factors. Factors for unquantifiable aspects can be included at several stages (and care needs to be taken that an excessive number of separate factors are not included). The envelope drawn over the PSD of the actual measurements can be is increased in amplitude to account for an estimate of the unquantified factors. Alternatively the shape of the APD can be factored in either amplitude and / or probability.

Relationship with Other Methods. The method differs from the other approaches set out here. However, it has some similarities with an old level crossing process than was sometime adopted before the ready availability of digital computers.

The MRS / FDS Approach

The vibration analysis tools known as Maximum Response Spectra (MRS) and Fatigue Damage Spectra (FDS) were originally developed within the French Atomic Energy Authority (Reference 11). The original purpose was as a means of comparing the affects of different vibration environments on equipment. The different vibration environments were compared in terms of their damage potential effects on notional (single degree of freedom) components within the equipment. The normal damage effects addressed were peak acceleration response relating to acceleration loadings, (by means of Maximum Response Spectra) and fatigue (by means of Fatigue Damage Spectra). In addition to peak acceleration loadings peak velocity and displacement can be considered.

Process. The basic process behind MDS and FDS is very similar to that that Shock Response Spectra (SRS). Essentially the relative response of a range of Single Degree of Freedom (SDOF) systems is computed. The Maximum Response Spectra is the highest value of response achieved by each SDOF when its base is excited by the waveform under investigation. The Fatigue Damage Spectra comprises the fatigue damage computed from the cycle amplitudes and the Palmgren-Miner hypothesis. Several specific methods can be used to compute MRS & FDS. Some of these make assumptions on the type of waveform (mostly sine, sine sweep or random gaussian) and permit significant savings in the computing times required. However, in recent years it has become practical to undertake MRS & FDS of arbitrary waveforms. Automated techniques exist to convert a pair of MRS and FDS into a test spectra in the form of a PSD. However, these are not always robust and a manual conversion is more frequent.

Example of Use of Method. Establishing test severities using this approach normally involves consideration of both MRS as well as FDS. However, these two parameters can be used together in several different ways. For the example used throughout this report Maximum Response Spectra and Fatigue Damage Spectra have been computed all flight conditions. For convenience these are placed into four groups straight and level flight, flight manoeuvres, take-off and landing (incl. climb and descent) as well as ground runs (taxi and engine start). The MRS are shown in Figures 19 to 22 and the FDS in Figures 23 to 26. Having established a database of MRS and FDS the next task is to combine the individual events to replicate a single flight. For the MRS this can simply be done by establishing the maximum values of all conditions that will be experienced. The outcome of this is shown in Figure 27 again a separation between the four groups of events has been maintained. However, it is clearly apparent from the Figure that Take-off and landing constitutes the most severe condition with straight and level flight the next most severe. Combining the FDS values is more complicated as the values need to be adjusted, from the measurement durations, to those required for the flight for which test severities are required. The FDS for the various events can then be summed together. With measurements from 40 separate events available the composition of the flight can be quite complicated. Figure 28 shows the resultant FDS for the 3 event groups (flight Straight and Level has been combined with flight Manoeuvres). The FDS for the full flight would be the sum of all four (although in reality that would be little different from the take-off and landing values). Figure 29 shows the test spectra derived from the worst case MRS. The test duration associated with this amplitude is shown in Figure 30. This was derived from the FDS for the full flight combined using an user specified flight profile. In a case such as this the process would normally be performed separately for take-off & landing, flight as well as ground runs. This would prevent excessive time compression. Shown in Figure 31 is the test derived from the FDS alone. This could be considered equivalent to the PSD for the full flight viz. a real time average level.

Assumptions / Limitations. The main assumption made when using SRS, MRS & FDS is that the real equipment responses can be represented by the response of a base excited single degree of freedom (SDOF) system. Whilst, this is not always the case, it is frequently a reasonable assumption. Further when computing MRS & SRS an assumption on the SDOF damping value needs to be made. However, the outcome of the calculations are more dependant upon the value selected for MRS than is usually the case for SRS. For FDS calculations a further three constant factors need to be set. Normally two of these factors are set to unity so play little part in the calculations. The fourth factor is the constant used in the

Palmgren-Miner fatigue hypothesis. The results are very sensitive to this latter factor, although work has shown FDS values can be easily modified for other values.

Advantages / Disadvantages. In theory MRS and FDS can compute the loadings and fatigue life of an SDOF in absolute terms. However, they are not usually used in that role mostly because of the limitations set out above. The real advantage of MRS & FDS is as a tool to compare the maximum response and fatigue effects of different excitations and environments. In such cases parameter variability has little real effect provided reasonable values of damping and fatigue constant are selected (and the same values used in all the calculations). The main disadvantage of FDS is the very long computation times necessary.

Repeatability. The repeatability of MRS is arguably as good as that for SRS. Theoretically if MRS calculations of random vibration measurements are been made then statistically quite a long record would be required to ensure maximum values are observed. Practically an estimate of likely errors is easily derived. A number of different numerical approaches are available to compute MDS & FDS. Moreover, some of these are simplifications of the basic approach and are limited to specific excitation types (broad band random or sine sweep). These different approaches have little real effect on the computed MRS values but can have significant effect on the FDS values. When used for comparison purposes (using the same method) this is of no consequence. However, this would not be the case if the comparison were from FDS computed using several methods.

Applicability. Fatigue Damage Spectra is only one of two tools (along with APD) that permits test durations to be established, for complicated environments such as road transportation, on any quantitative basis. Additionally FDS and MRS permit comparison of the effects of significantly different types of excitations which cannot be done reliably with any other current method.

Traceability. In most cases the computed MRS and FDS can be adjusted for different damping and fatigue parameters. Moreover, the parameters used are generally quoted. However, the effect of different computation method on FDS is not readily accounted for and the method used is frequently not indicated. As MRS and FDS require significant computing effort they are not usually undertaken until other methods have been used to establish data validity.

Uncertainty Factors. Factors for unquantifiable aspects can be included at several stages. Amplitude Factors may be included on the Maximum Response Spectra whilst time based factors can be included on the FDS.

Relationship with Other Methods. The FDS method differs markedly from any other commonly used approach. The MRS method is essentially the SRS method but applied to vibration rather than shocks.

Conclusions

All the methodologies encompassed by this review have been used to establish test severities for inclusion in national or international standards over the past 20 years. Some of the methodologies are used extensively by test specifiers to establish tailored requirements. A number are used more frequently in some countries than others. Few papers exist which address the advantages and disadvantages of various methods. This review has not made specific recommendations as selection of the most appropriate method as that will depend upon the type and form of data been analysed.

The conventional Power Spectral Density approach is bar far the most widely used method of those considered in this review. Although widely used for many years and probably the simplest method, it has a number of significant limitations which are not always met. In particular the approach is applicable only when the data are stationary. Ensuring this condition is met for real world data can be difficult as vehicle speed and surface type result in changes in vibration amplitude and characteristics. Several of the other methods addressed by this review are modifications of the conventional Power Spectral Density approach intended to alleviate this limitation.

The Peak Hold spectra approach allows some of the effects of data non-stationarity to be established. The method can easily be used along side the conventional Power Spectral Density approach with little additional computational overhead. For this reason the Peak Hold spectra approach is often used to establish the existence of non-stationarities. However, the method is weak at quantifying these effects as the peak hold spectral values are statistically poor. Care also needs to be taken in converting the Peak Hold spectra into a test spectra.

The Foley approach was developed specifically to allow the use of real world transportation data from multiple sources. The approach can be partly automated allowing the cost effective inclusion of large amounts of data. The approach allows the inclusion of real world data from a wide of different vehicles by both frequency and time averaging. The conversion to a test spectra also compounds this averaging. The consequences of these aspects are to generate an “average” rather than necessarily worst case severity. This is partly, but not fully, offset by selecting only the most severe 10% of the data for inclusion. Whilst, test severities derived from the Foley approach were, and still are, included in a number of national standards, the approach is rarely used today. This is partly a consequence of poor knowledge of the details of the method and partly because of the difficulty in its implementation.

The Aberdeen proving ground approach was developed to counter some of the problems of the Foley approach. It approach was intended to be a largely automated method. The original intend was to permit the combining of data acquired on test tracks from a variety of vehicles and measurement locations. Not only does the approach not intrinsically overcome the need for stationary data, it requires that data inclusion is limited to quite specific test tracks and speeds if the combining of data is to be effective. When, the approach has been used on non-test track data, it has not always proved successful. In particular the derived test severity does not necessarily ensure worst case conditions are encompassed. Although test severities derived from this method are still included in a number national and international standards, it is rarely used outside a small group of its proponents.

The APD approach can be used on real world non-stationary data were the non-stationarity relates to amplitudes but the frequency response characteristics do not change significantly. As this encompasses a number of situations the APD approach has potential in a range of circumstances. Although the APD approach can be used on its own, it is more frequently employed along side the conventional PSD approach. The approach is based upon a statistically sound methodology and the bulk of the data processing can be undertaken using a largely automated process. Nevertheless, the final stages require some expertise in identifying the actual test severity.

The final approach addressed in the review are the combined use of Maximum Response Spectra (MRS) and Fatigue Damage Spectra (FDS). Until recently this approach was limited by the extensive computing required in the generation of MRS and FDS as well as the lack of commercial software. If the appropriate processes are used the combined MRS and FDS approach can be used on real world data and ensure a test severity is generated which both encompasses the worst case amplitude experienced along side a realistic test duration. The combined MRS and FDS approach is becoming more commonly used as commercial software is now available which allows computation in a realistic period.

Although this review addresses the various approaches separately, it is not unknown for test specifiers to utilise several along side each other. Indeed information for the conventional PSD approach, the peak hold approach and the first stages of the Aberdeen proving ground approach can be established with little additional computing requirements from undertaking each separately. Although computing values for the APD approach requires the separate computation of Amplitude Probability Density, this is common (and useful) undertaken for data verification purposes. The combined MRS and FDS approach is only likely to be undertaken on selected data for some time to come.

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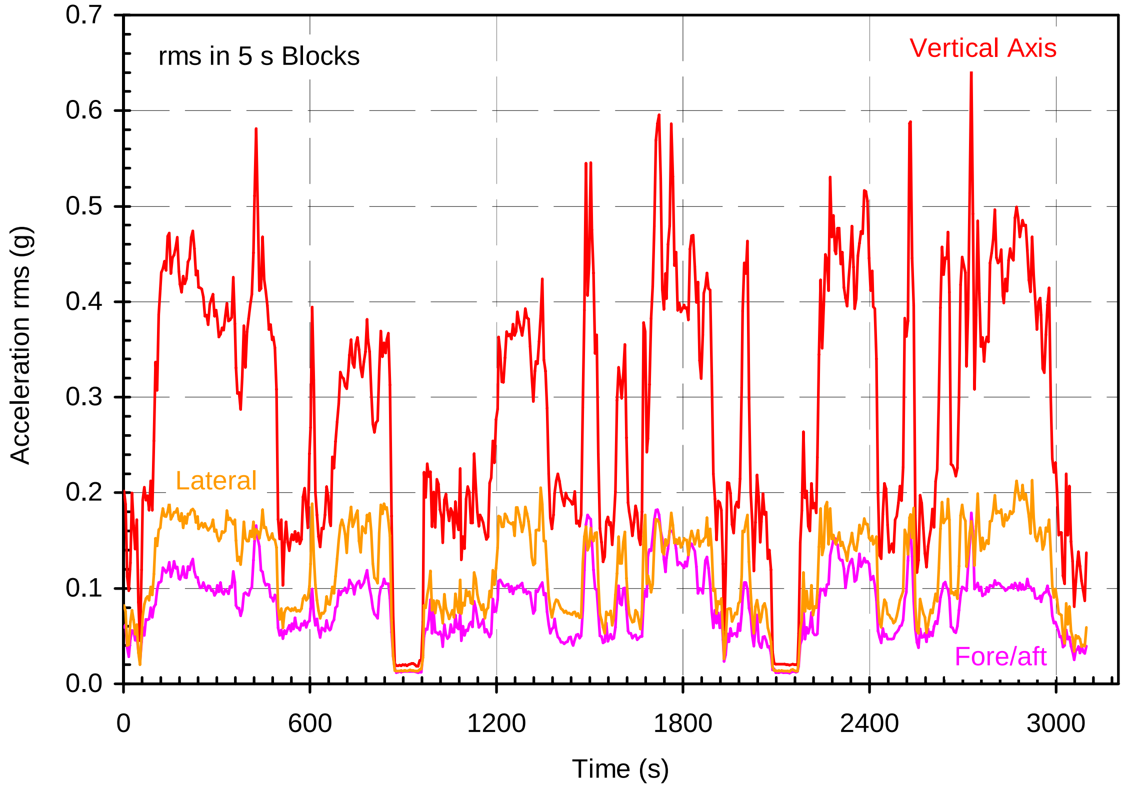

Figure 1 Typical Variations in Vibration Severity in a Real Road Journey

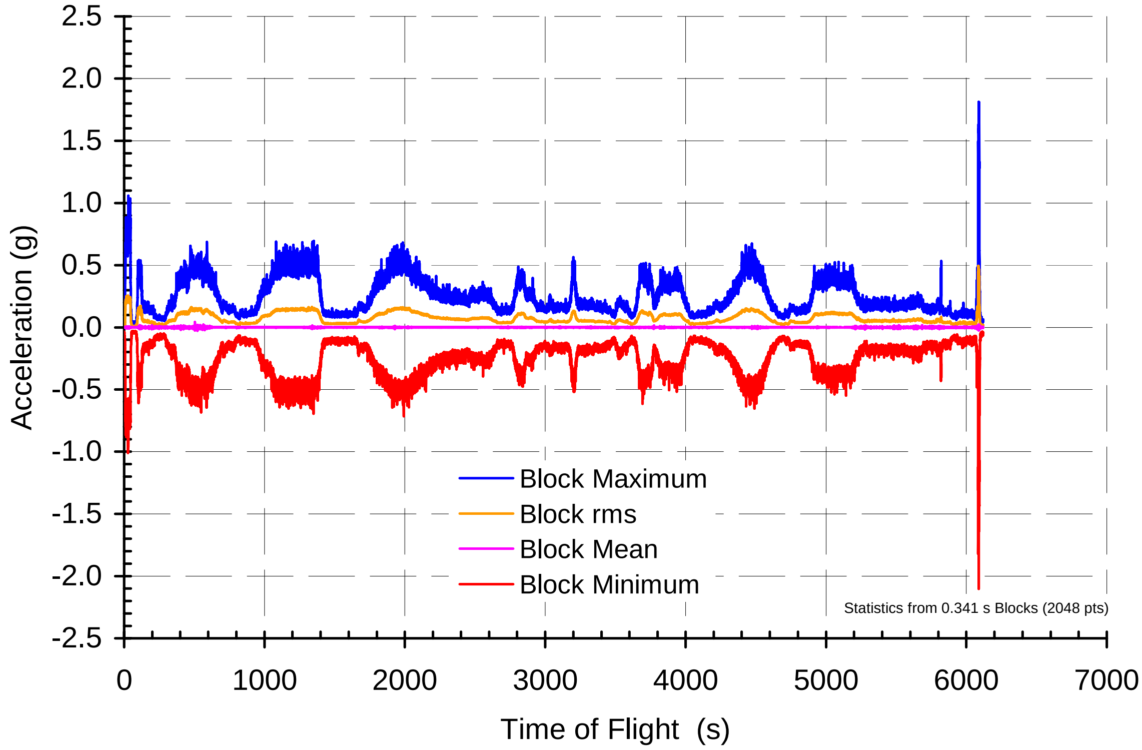

Figure 2 Block Statistics For The Full Aircraft Flight

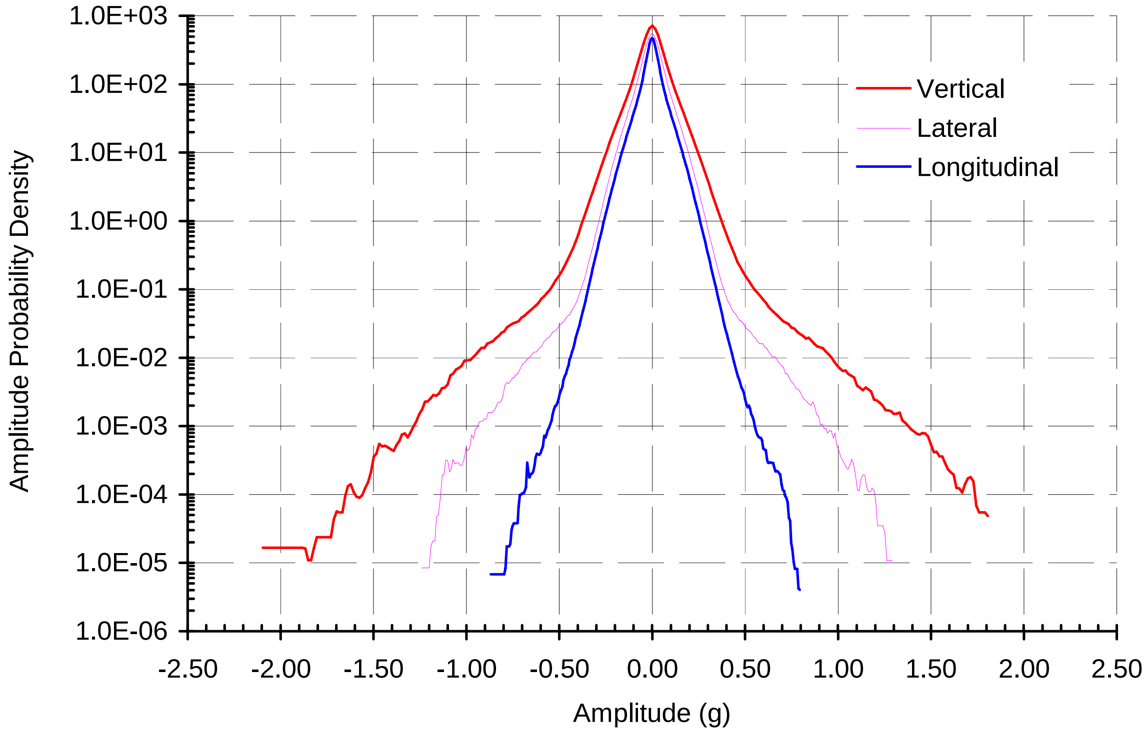

Figure 3 Amplitude Probability Densities for Full Aircraft Flight

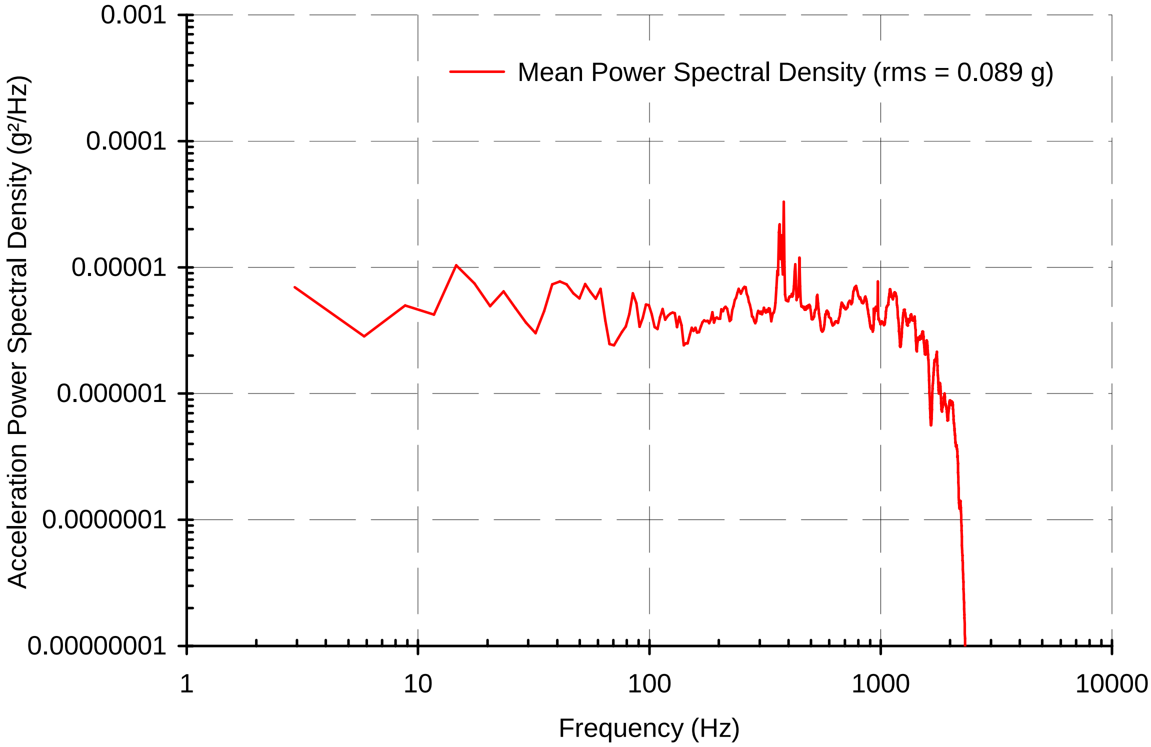

Figure 4 Power Spectral Density For a Full Aircraft Flight

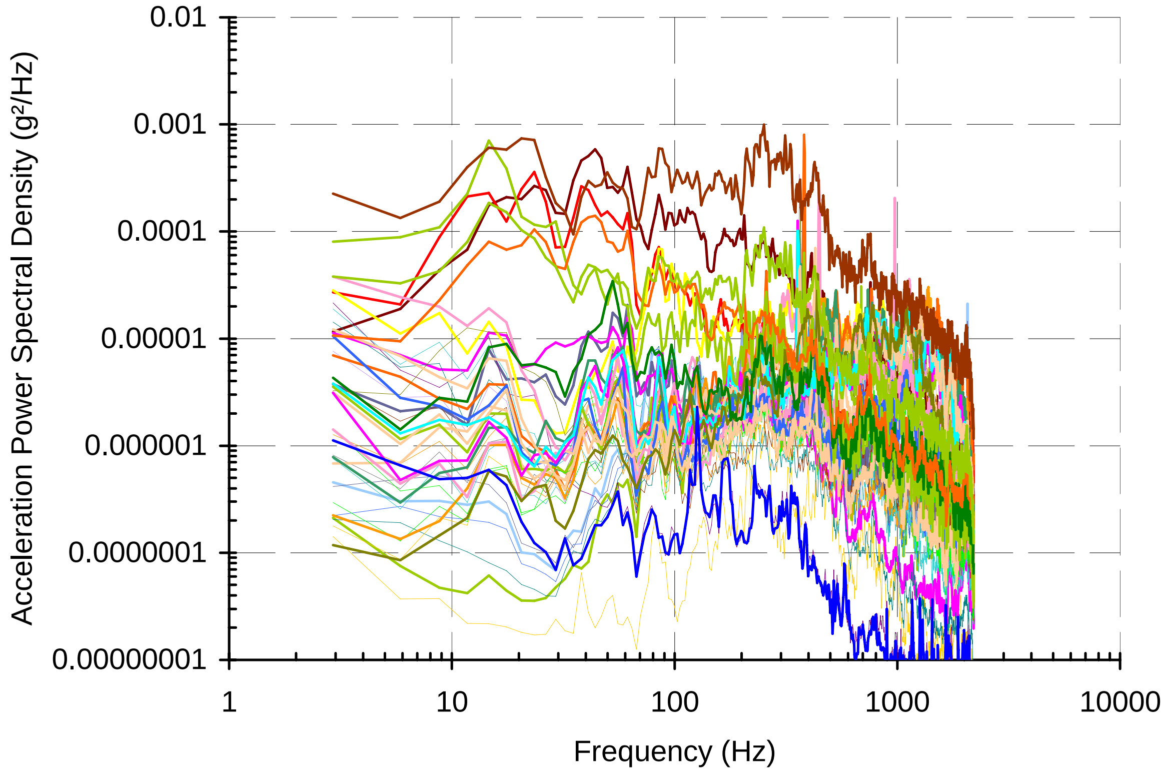

Figure 5 Power Spectral Densities for 40 Selected Flight Events

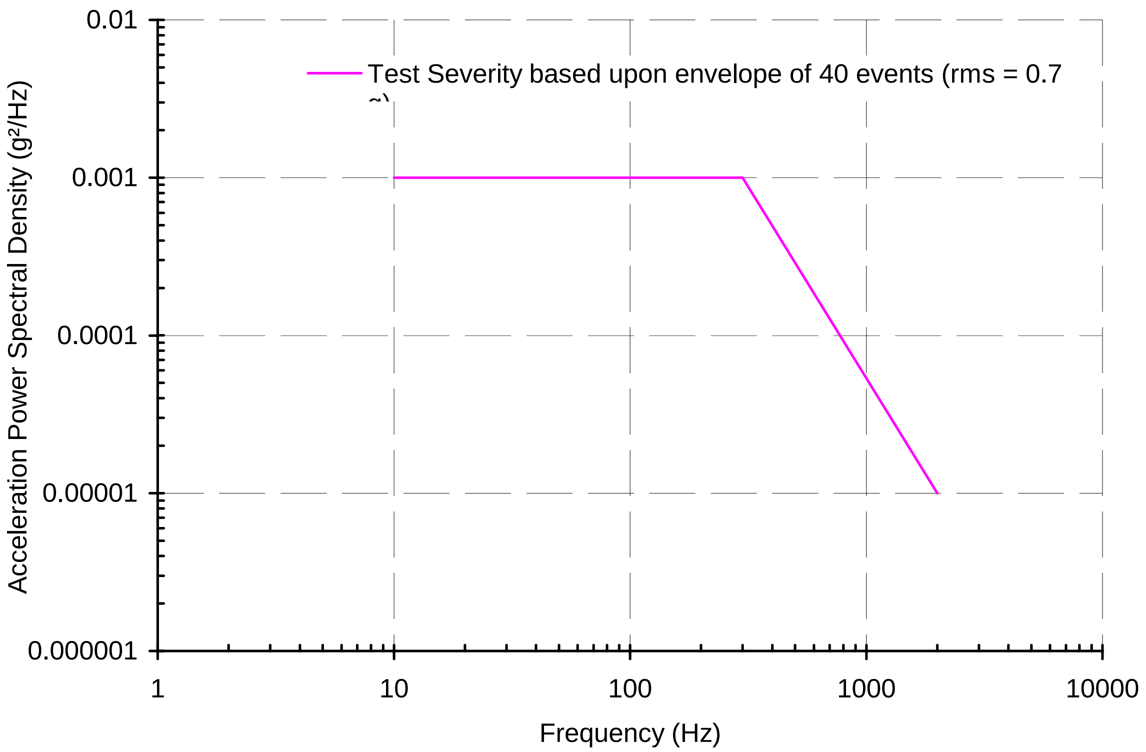

Figure 6 Derived Envelope of PSDs for 40 Flight Events

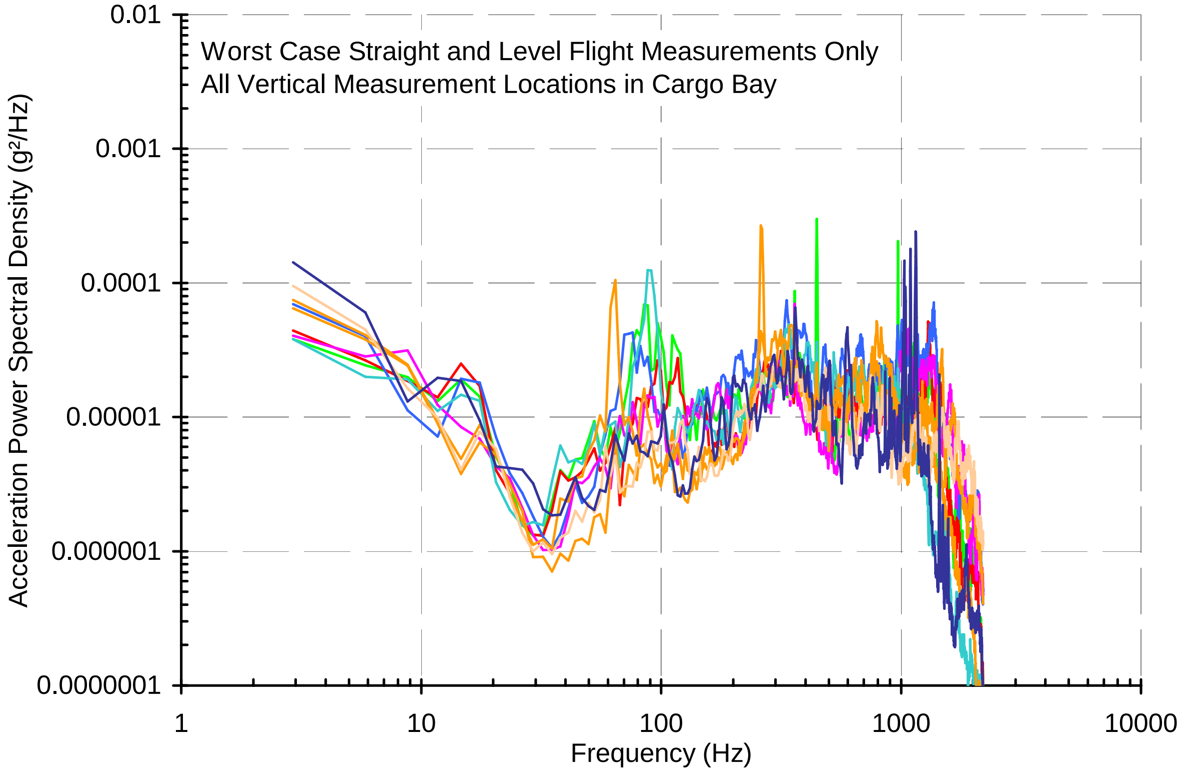

Figure 7 PSDs For Worst Case Straight and Level Flight

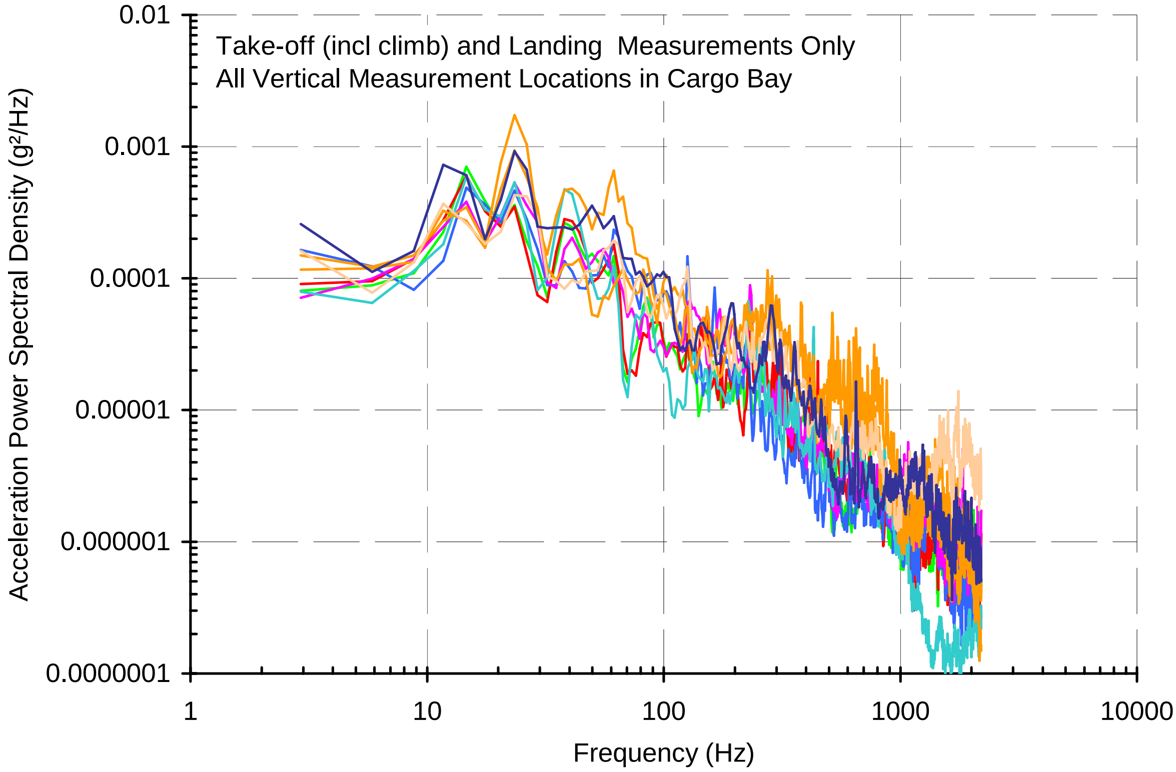

Figure 8 PSDs For Take-off and Landing

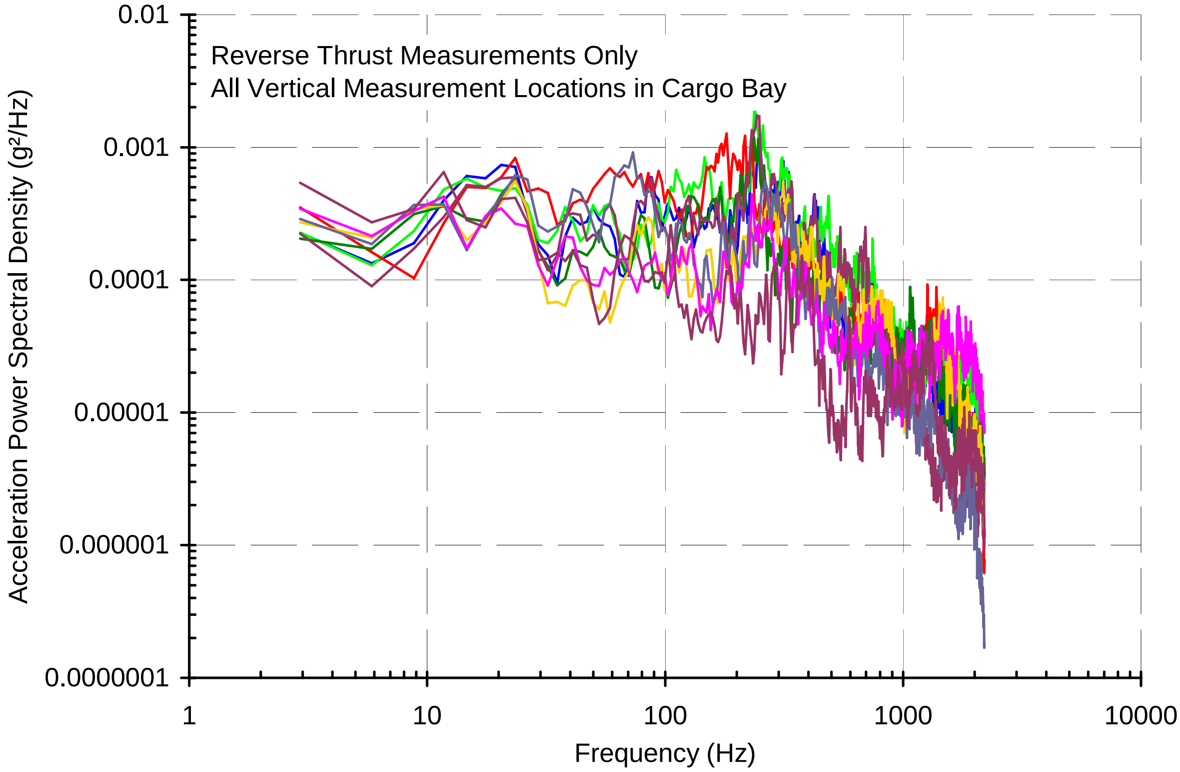

Figure 9 PSDs For Reverse Thrust Event

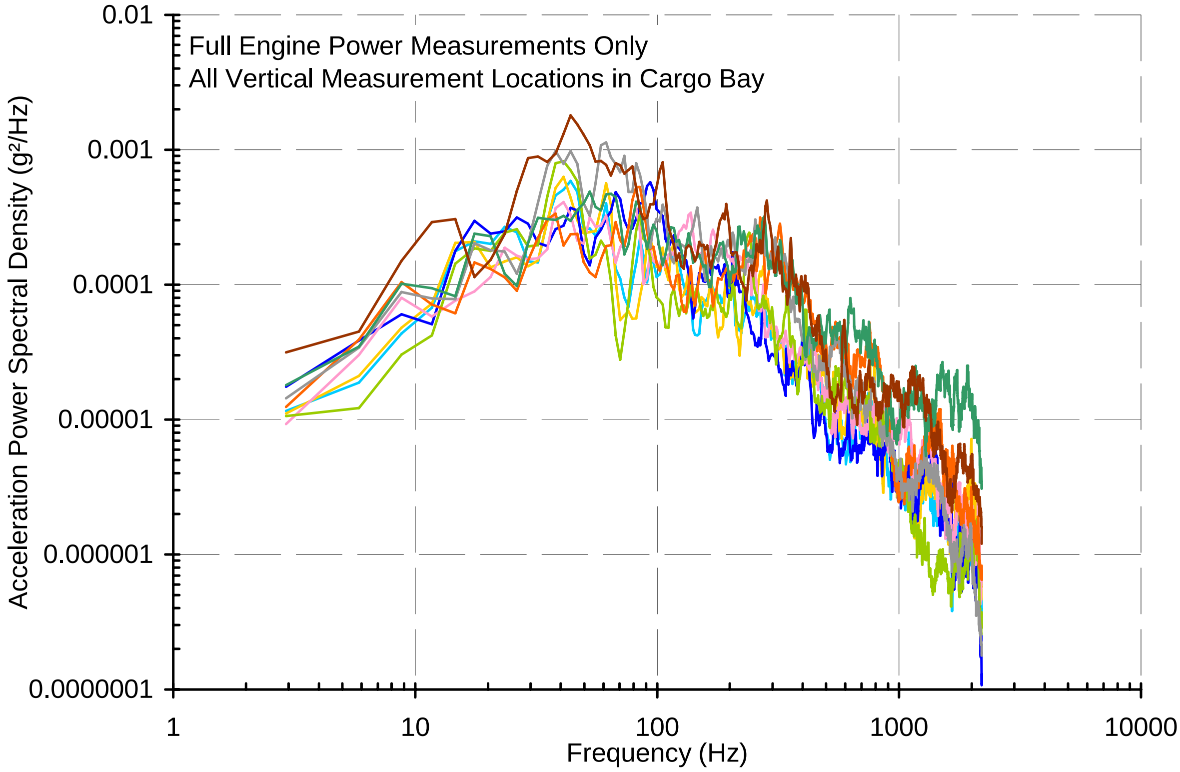

Figure 10 PSDs For Pre-Flight Full Engine Power Event

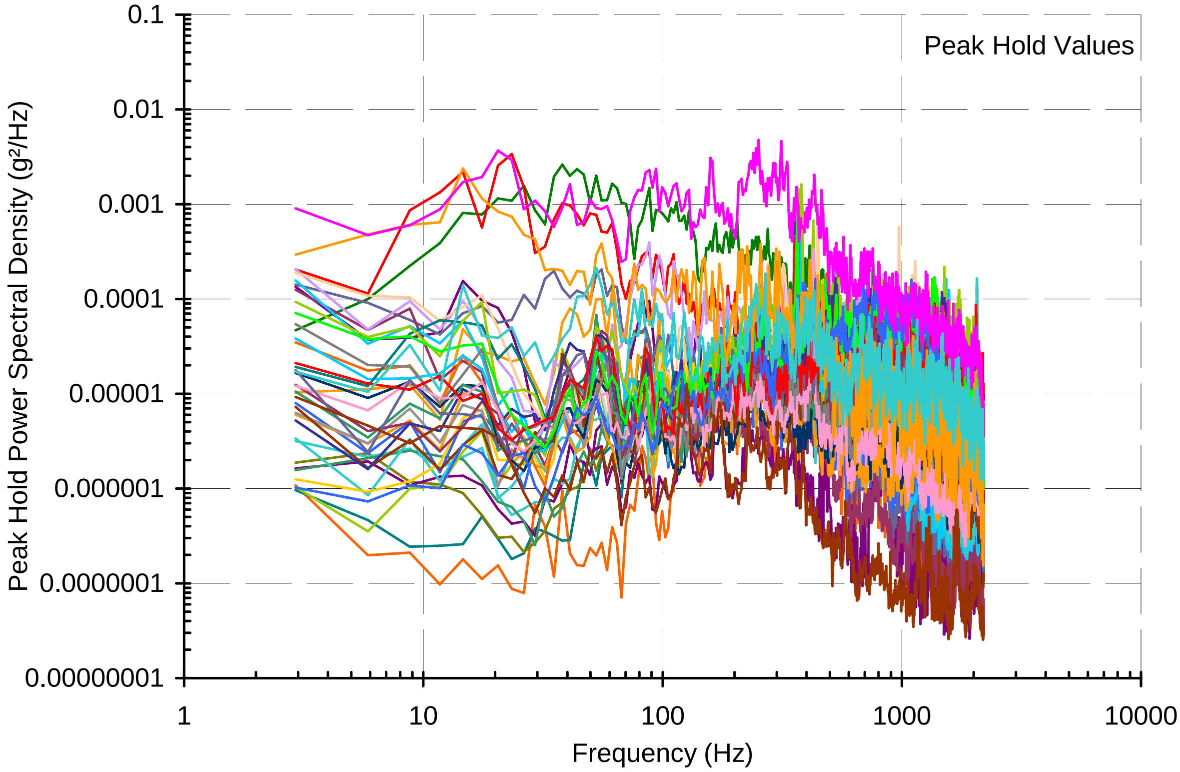

Figure 11 Peak Hold Spectral Densities for 40 Flight Events

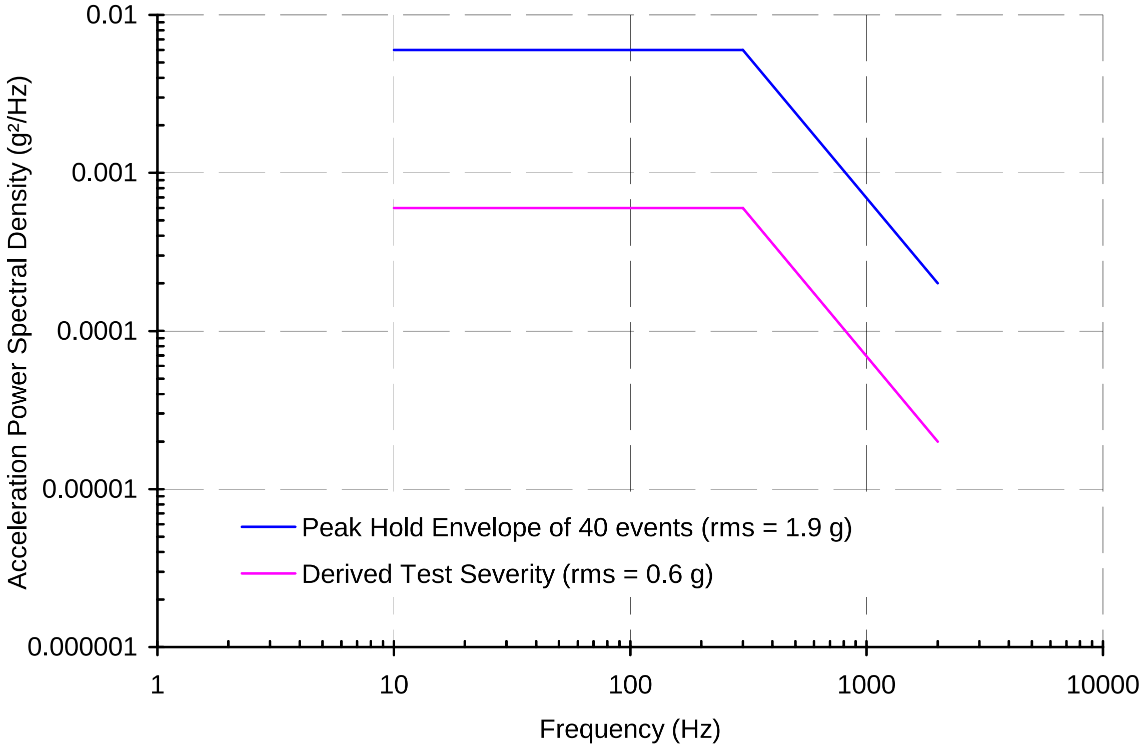

Figure 12 Derived Peak Hold Envelope and Test Spectra

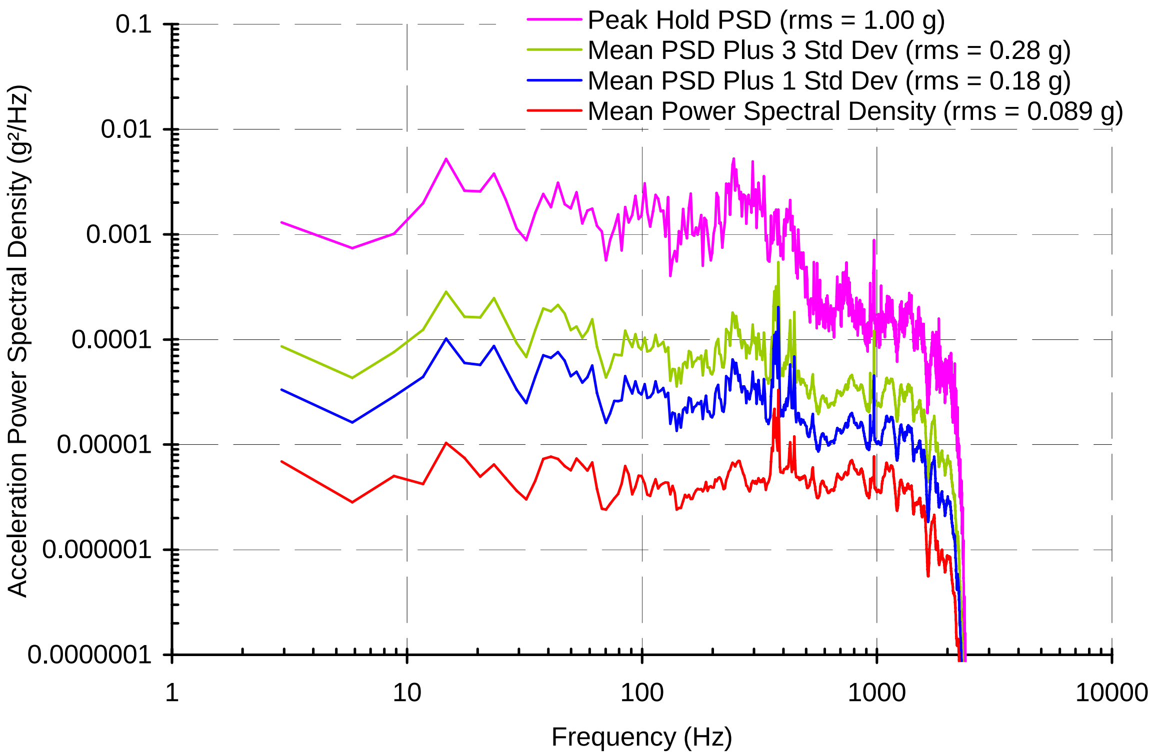

Figure 13 Various PSD Statistics Computed for Full Flight

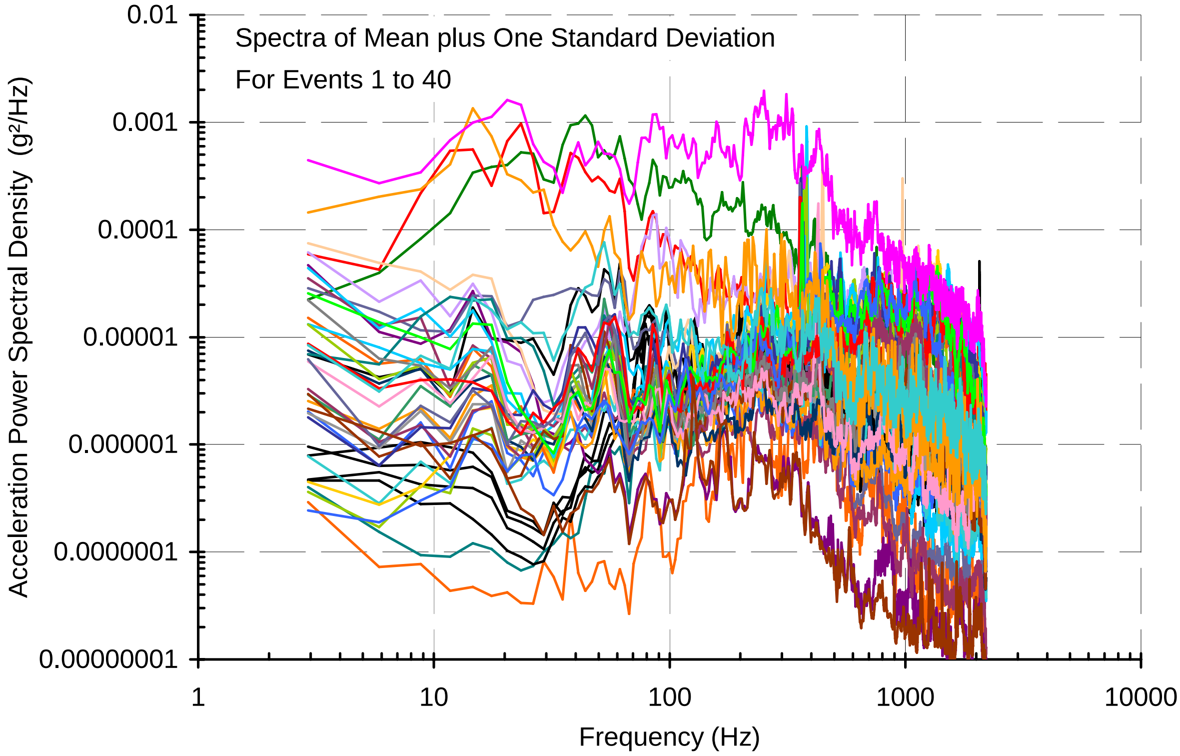

Figure 14 Spectra of Mean Plus One Standard Deviation for 40 Flight Events

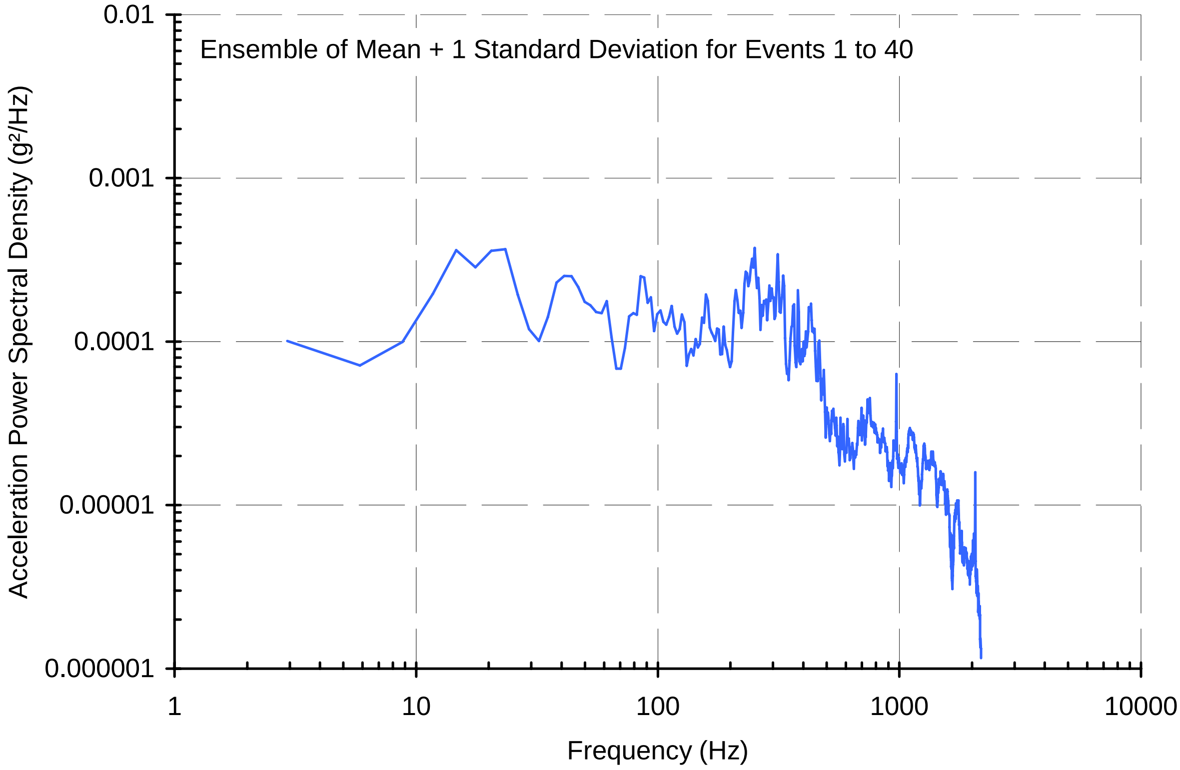

Figure 15 Mean Plus One Standard Deviation of 40 Events for One Location

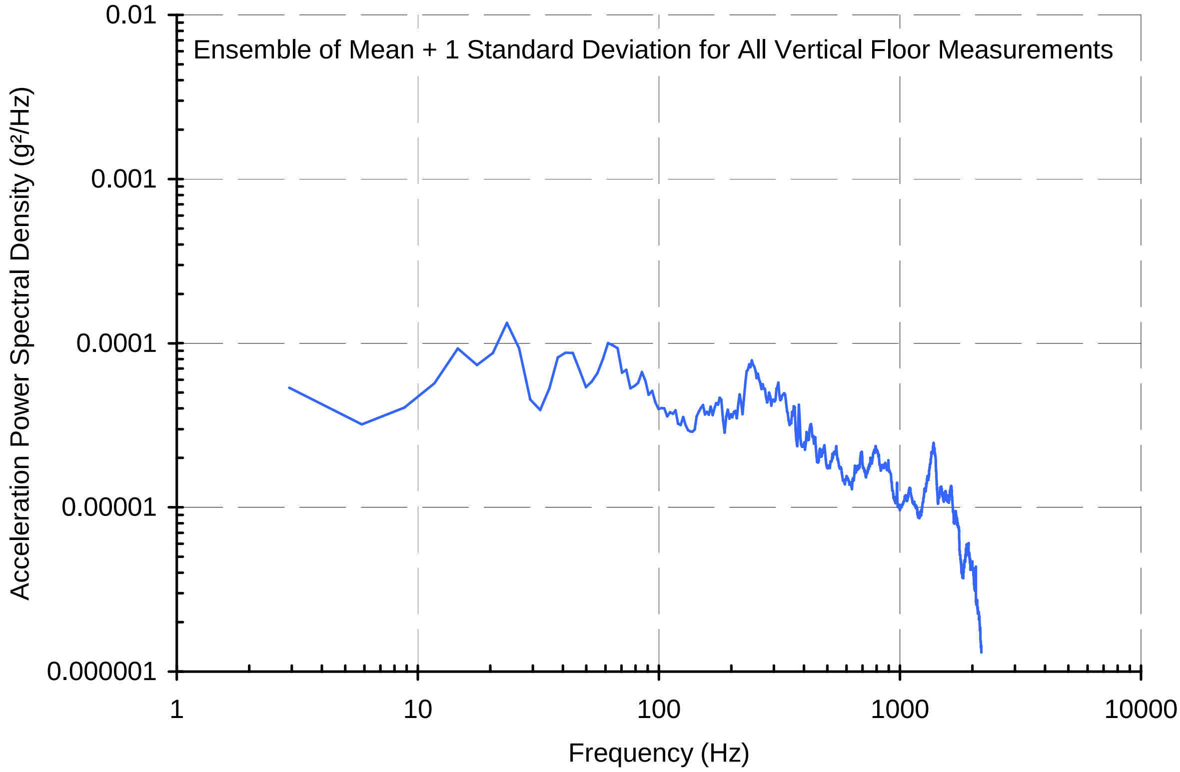

Figure 16 Mean Plus One Standard Deviation of All Vertical Measurement Locations

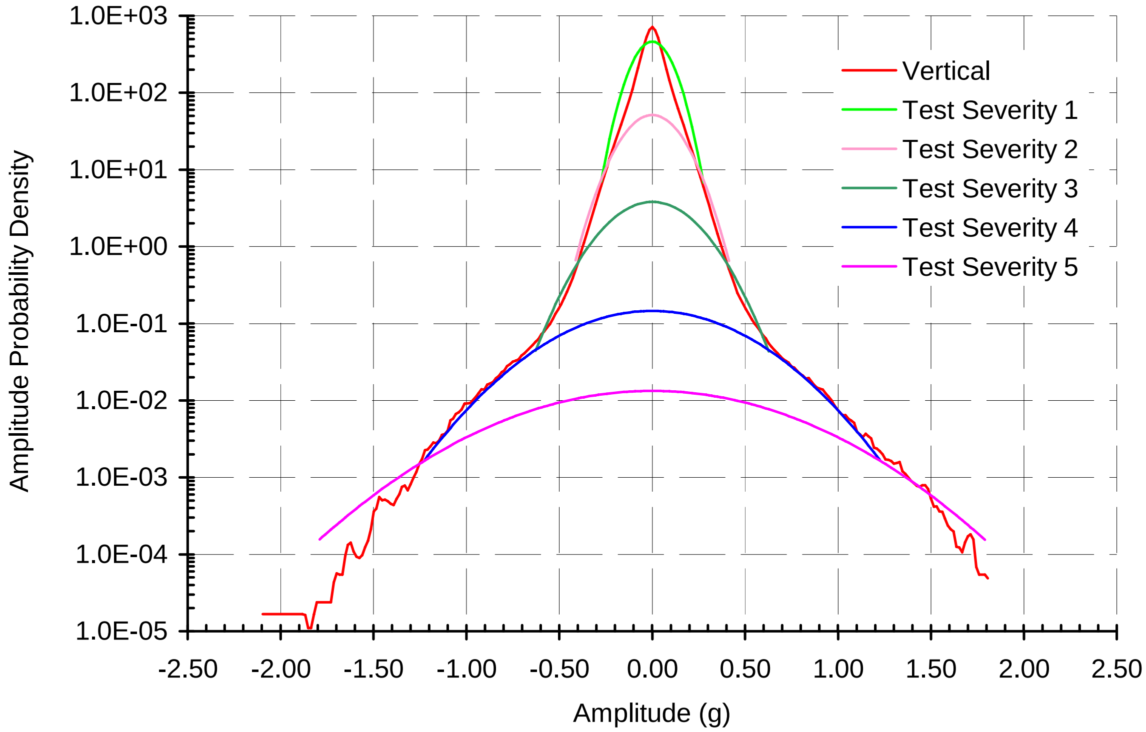

Figure 17 Curve fit of Full Flight APD

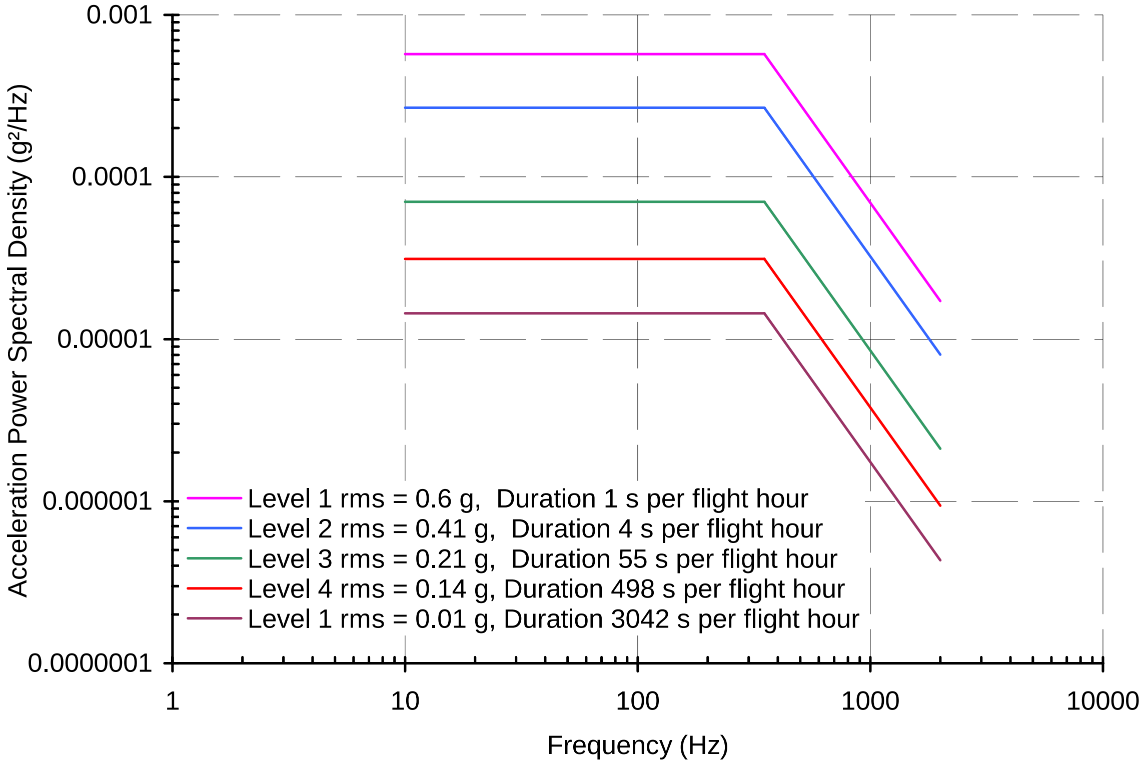

Figure 18 Test Severities and Durations Based upon APD

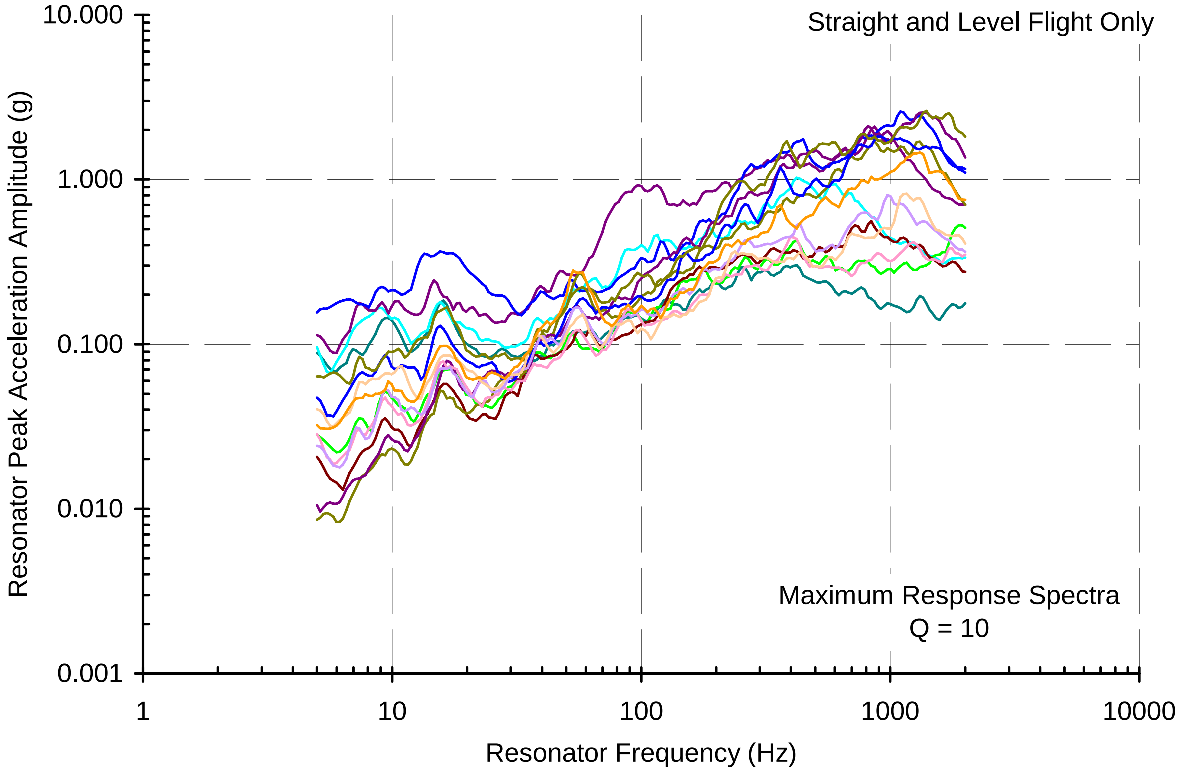

Figure 19 MRS From Straight and Level Flight

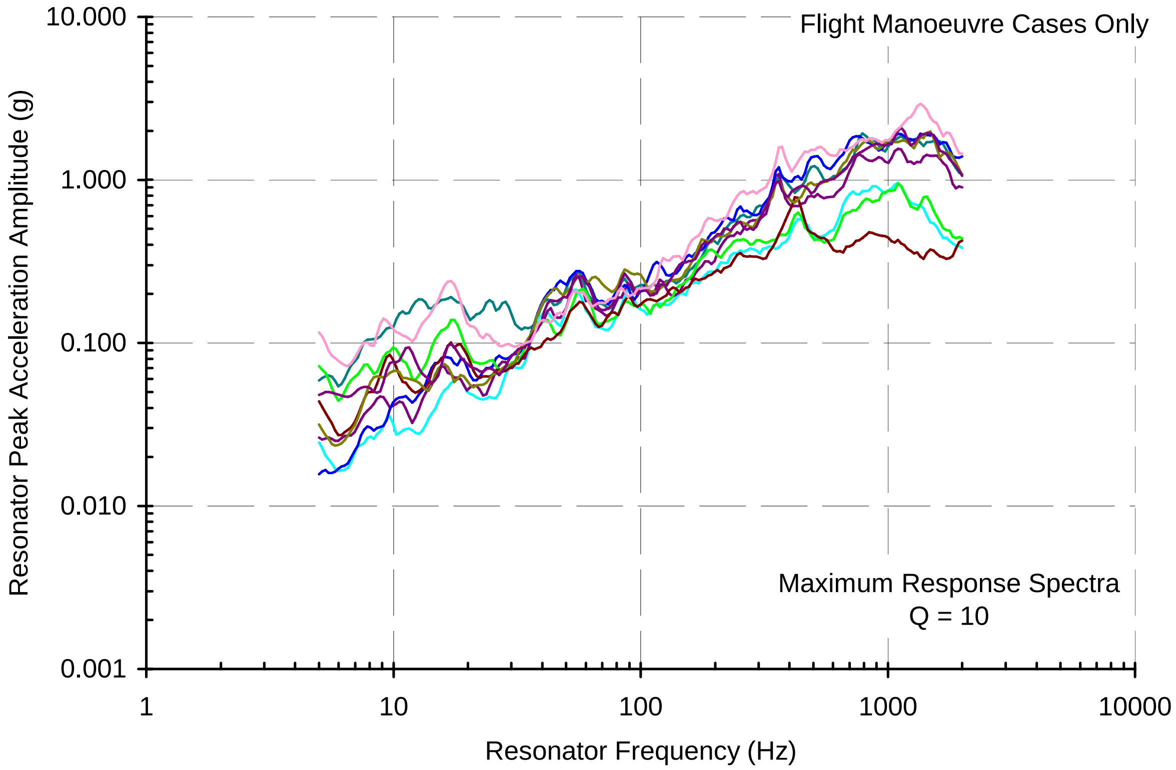

Figure 20 MRS From Flight Manoeuvre Cases

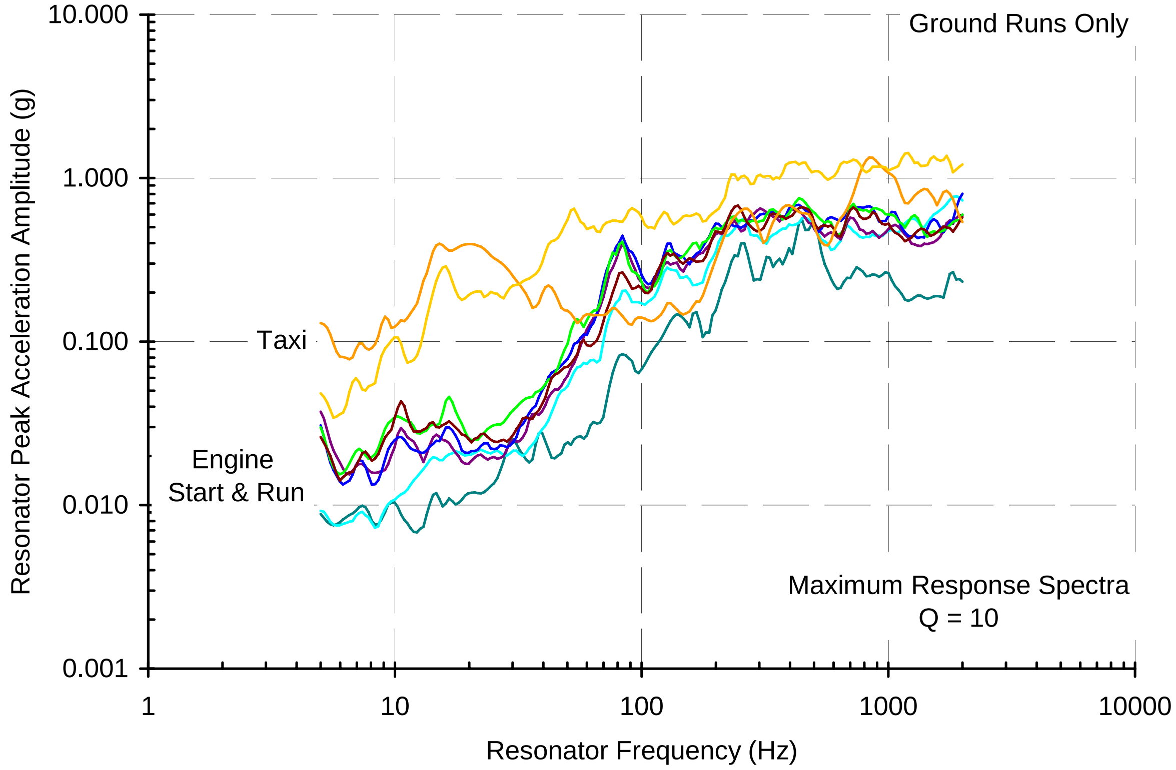

Figure 21 MRS From Ground Runs

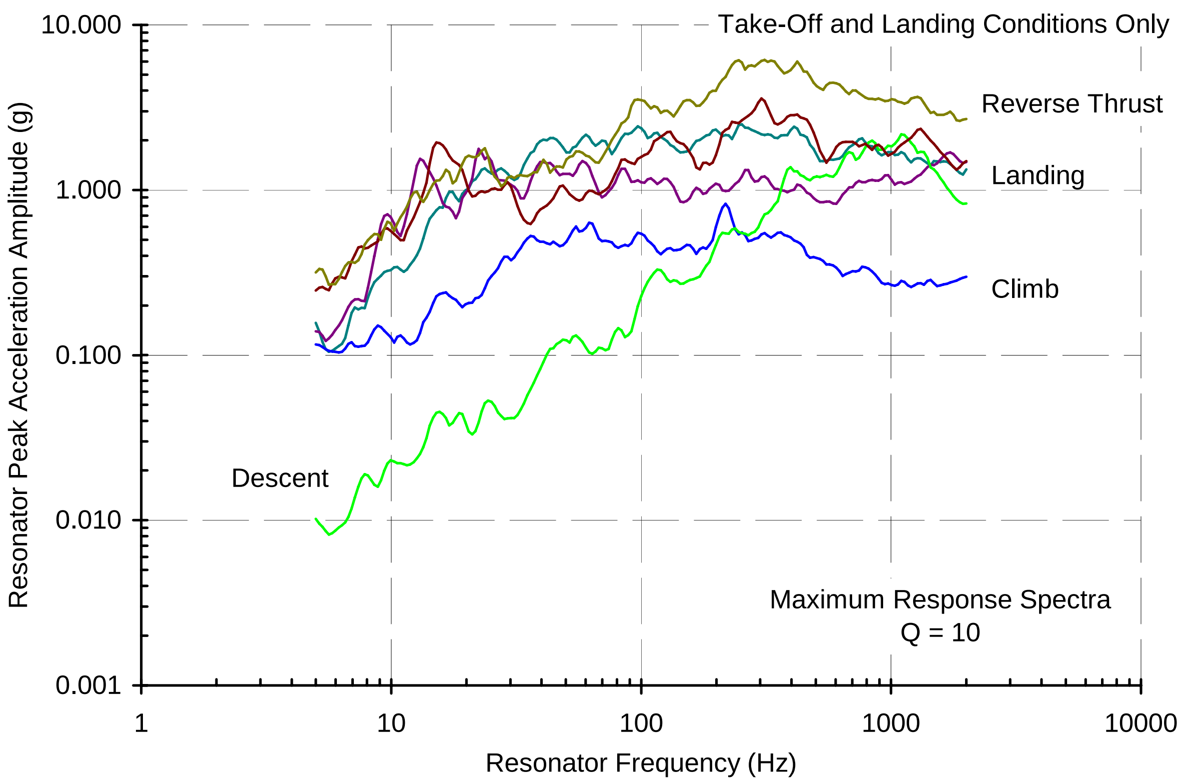

Figure 22 MRS From Take-off and Landing

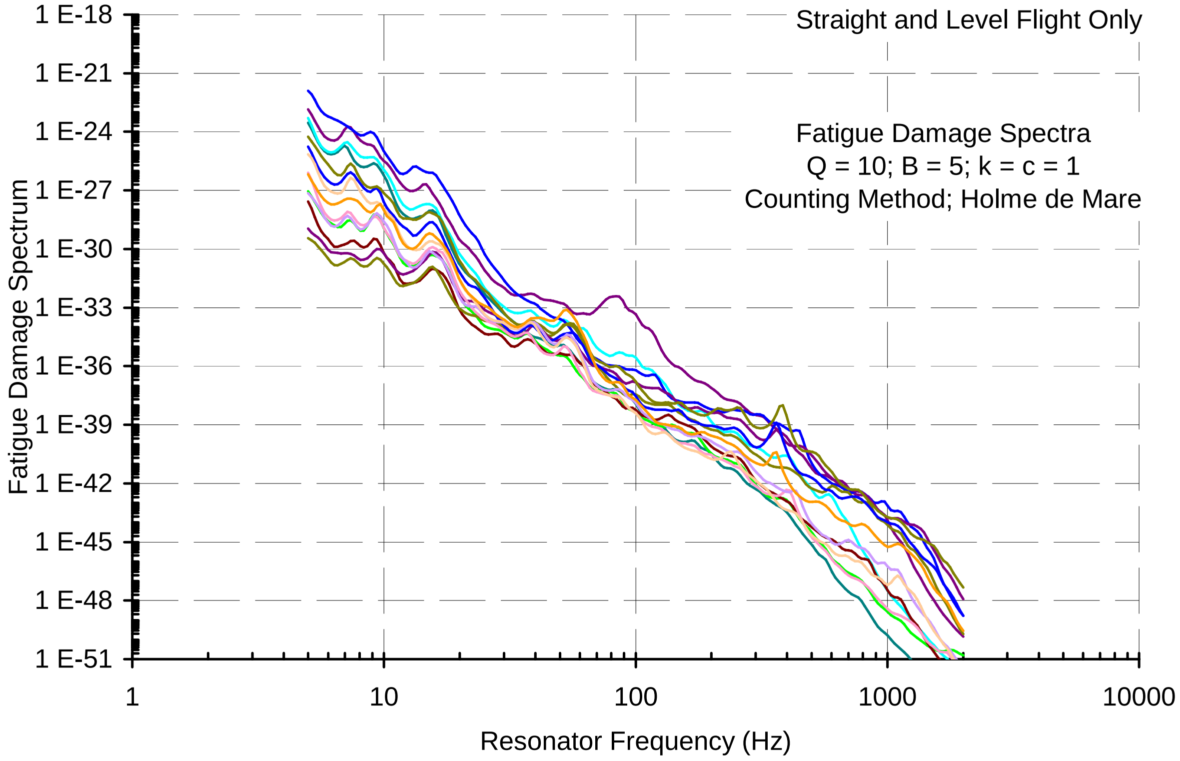

Figure 23 FDS From Straight and Level Flight

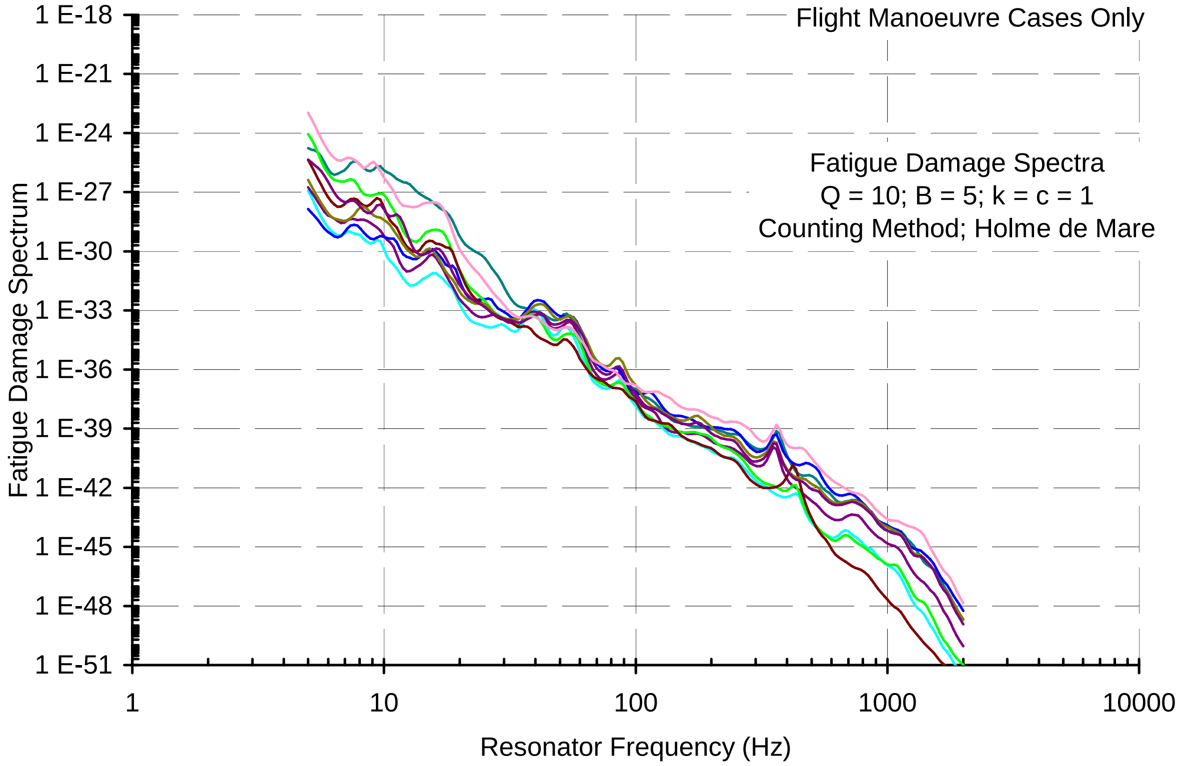

Figure 24 FDS From Flight Manoeuvre Cases

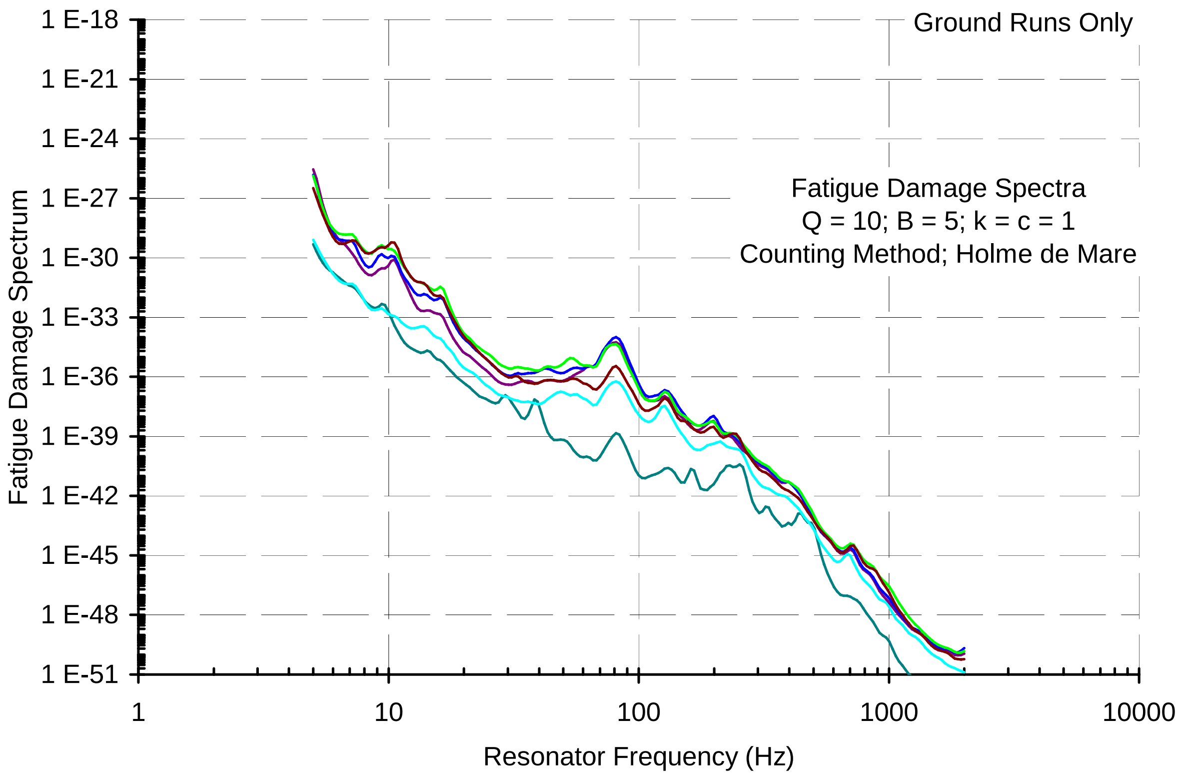

Figure 25 FDS From Ground Runs

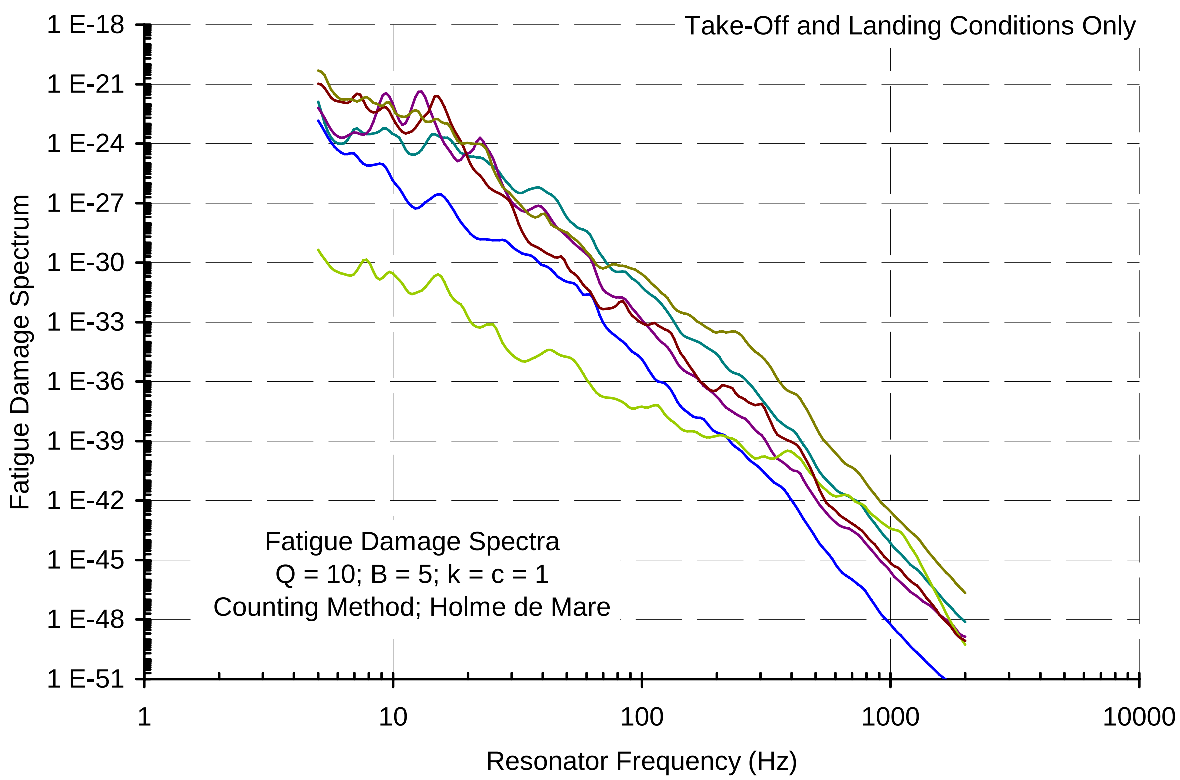

Figure 26 FDS From Take-off and Landing

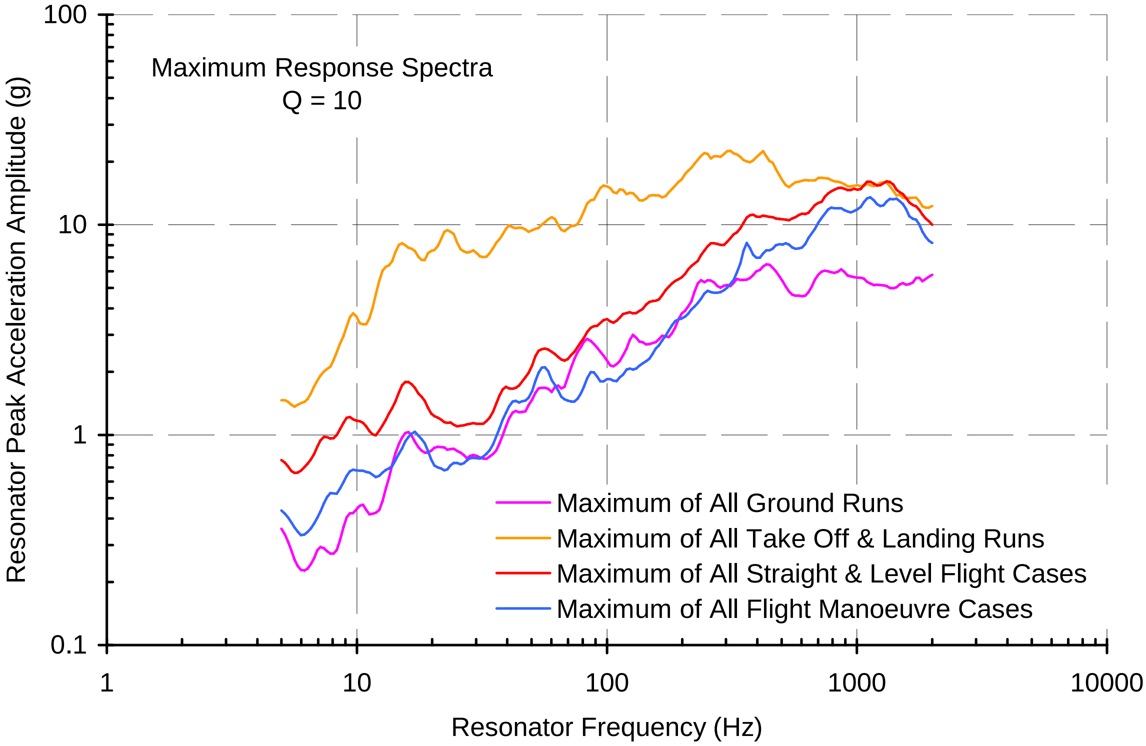

Figure 27 Envelope MRS For Each Group of Cases

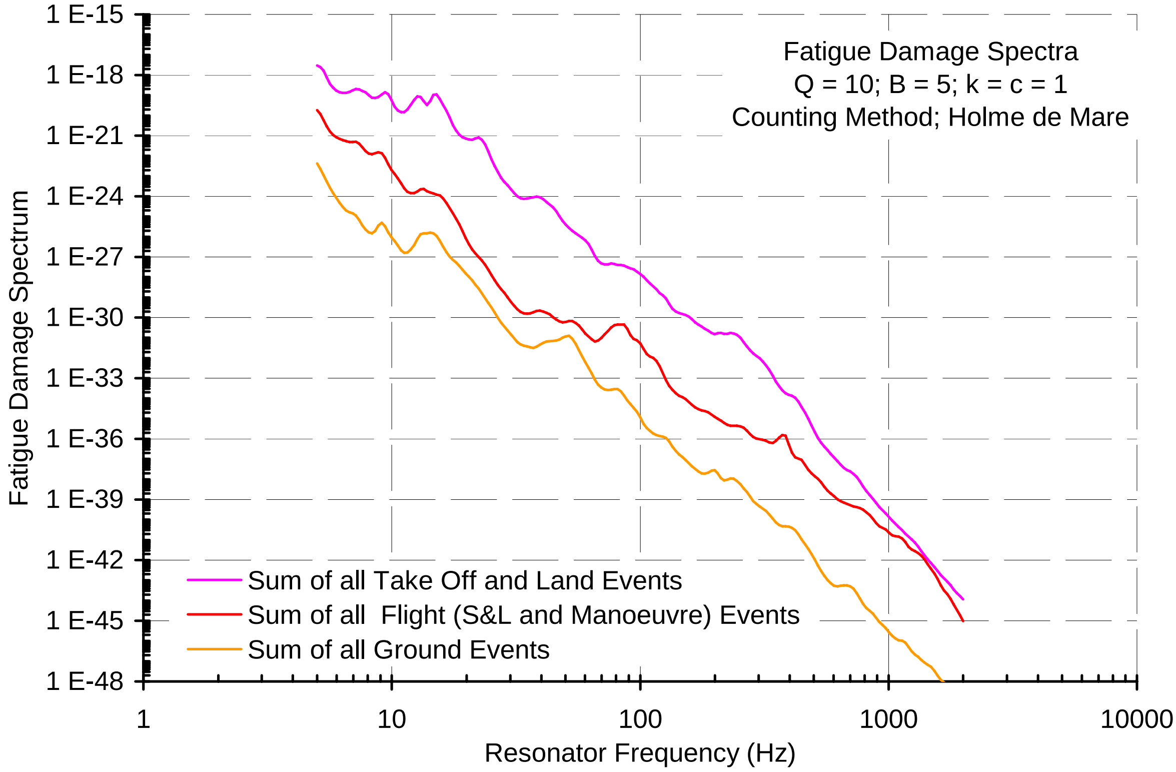

Figure 28 Sum of FDS For Each Group of Cases

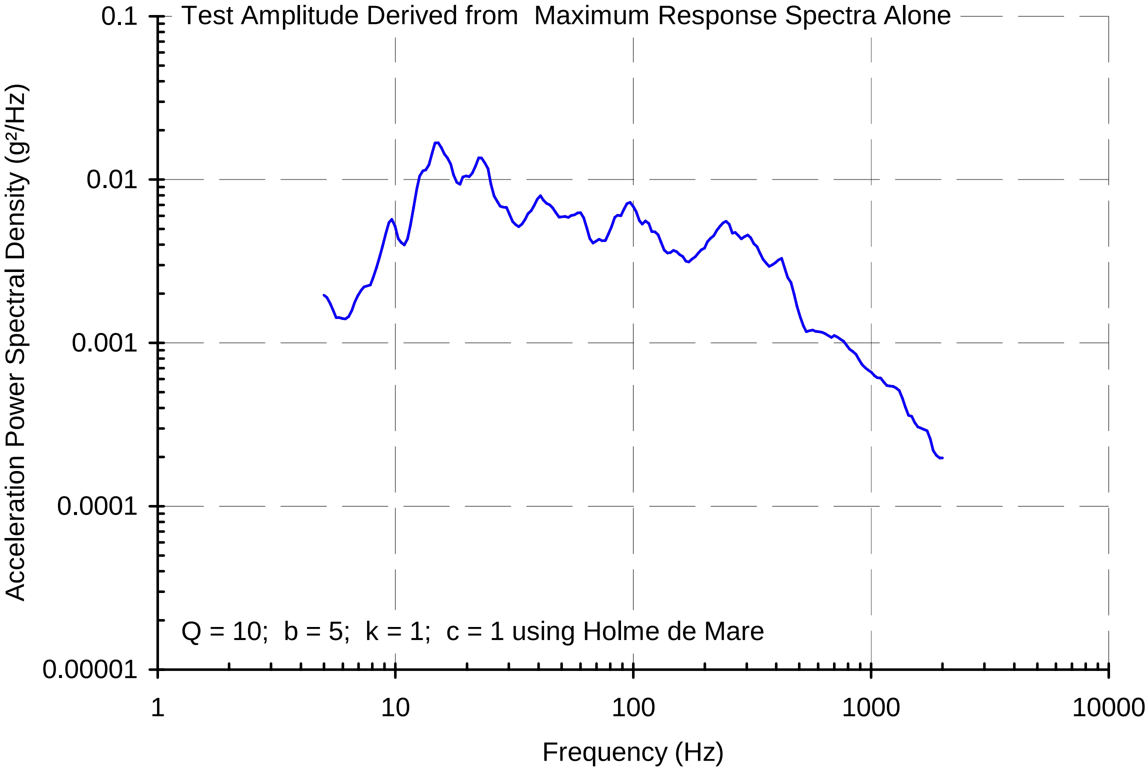

Figure 29 Test Severity Derived From MRS Only

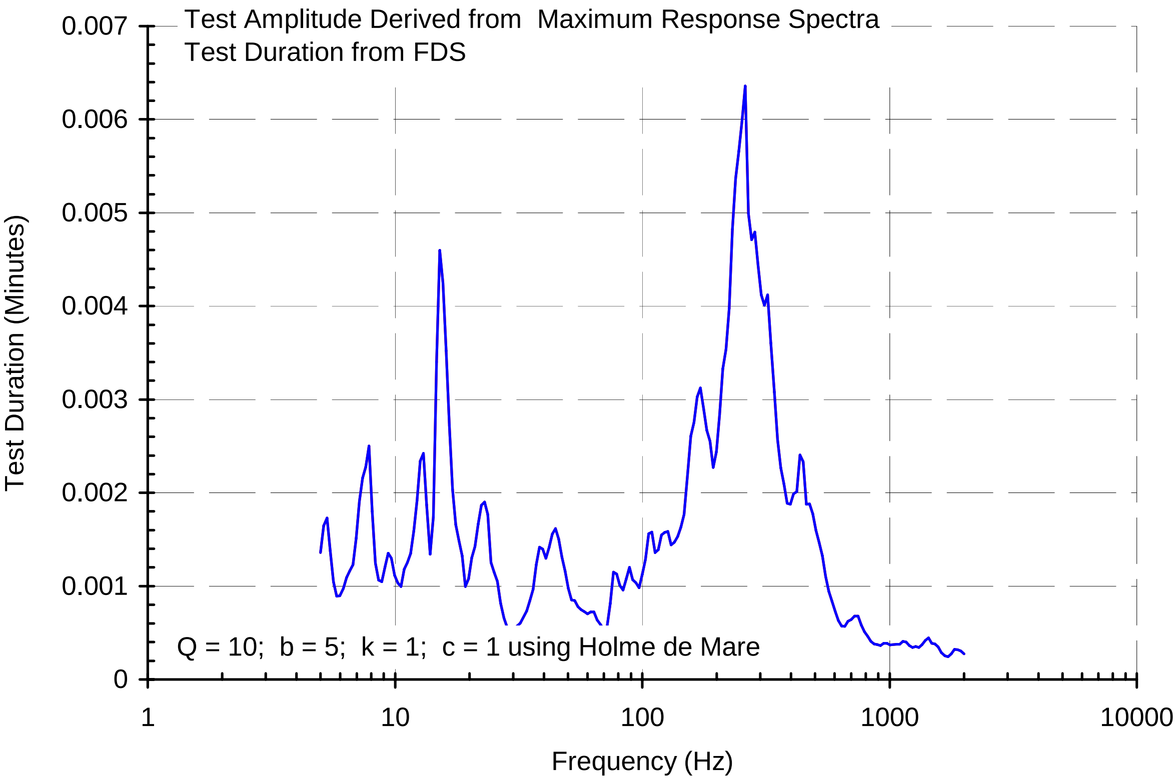

Figure 30 Test Duration Based For MRS Derived Severity Using FDS For Duration

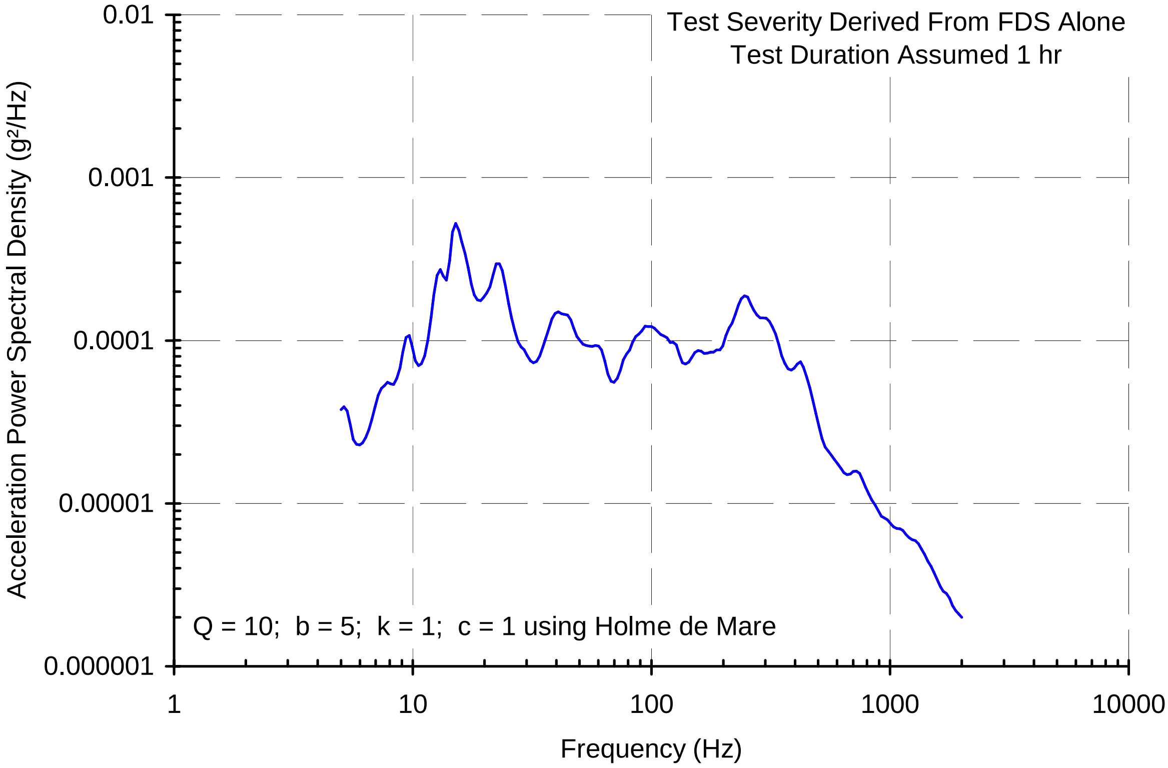

Figure 31 FDS Derived Test Severity