A Comparison of the Effects of Transportation Test Severities.

May 2001

By David Richards

Introduction

1. A number of National and International vibration test specifications contain different severities for replicating the effects of transportation. These differences are not just in terms of vibration amplitude and duration but also the type of test used. Although most modern test specifications adopt random vibration based requirements, some specifications permit the use of older sine sweep testing. In some cases these are permitted as valid alternatives. However, direct comparison of sine and random testing is notoriously difficult.

2. The purpose of this paper was to facilitate a comparison of different severities using the Fatigue Damage Spectra and Maximum Response Spectra methodology. The comparison contain in this paper was initiated to compare a sine sweep vibration test for general transportation that was set out in the UK Defence Standard 00-35. However, it was expanded into a similar comparison for a number of additional common test specifications.

Background

3. The Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity set out in Chapter 2-01 paragraph 5.8 is stated as “applicable to packaged materiel, when subject to transportation by road, rail air and/or sea between the manufacturer, ordnance depots and forward bases”. The test is a sine sweep type vibration test which predates Def Stan 00-35 by many years. The severity was reproduced in Def Stan 00-35, essentially unmodified, from the earlier Def Stan 07-55. However, the test almost certainly also pre-dates even that standard. The severity is reproduced in other UK defence standards notably the packaging requirements of Def Stan 81-41. At the time Def Stan 07-55 was published similar, but not identical, tests existed in other national and international environmental testing standards viz. Mil Std 810, BS2011. In recent years a number of these similar tests have either been replaced or random alternative included.

4. Generally the severity of the similar test in commercial standards are lower than those in defence standards (typically 1.5 g rather than 2 g from Ref. 2). However, for most commercial applications the severity of even those lower level tests has been found to be excessive. The EU funded SRETS project (Ref. 3) highlighted the cost of using excessive severities, on both packaging and transportation. The study also highlighted a marked difference between test severities intended for commercial equipment and those for military applications.

5. For military equipment the use of a generic transportation severity, in some testing standards, has been superseded because of changes in philosophy that occurred in the late 1970’s. At that time a change of testing philosophy occurred from “ruggedness test” approach to one with the intent of replicating the actual environmental conditions. As this change can have significant cost implications, Def Stan 00-35 adopted a more pragmatic approach, and included both these different philosophies. Specifically it sets out ruggedness type tests in Part 3 and more application specific severities in Part 5 (for dynamic conditions) and Part 6 (for induced climatic conditions). The increased use of Commercial Off The Shelf (COTS) equipment, in recent years, for military applications has confirmed the pragmatic approach adopted by Def Stan 00-35 to be prudent.

6. Several arguments are commonly put forward for the retention of the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity. The most significant of these is that with a single test the package and equipment manufacturer can demonstrate that packaged equipment is able to survive essentially any form of commercial and military transportation. From the view point of the

end user, the use of the “Transportation of Materiel” test has demonstrated, over the years, that no real limitations on transportation of the equipment are needed. The test appears to require no knowledge of the dynamic characteristics of the packaged equipment for it to be applicable (other than whether is mass is greater or less than 150 Kg) and seems to be applicable to good and bad package designs (specifically it seems adept at identifying poor and bad package designs).

7. The advantages of the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity are clearly only available if the packaged equipment is able to survive the test and the test is accepted as encompassing all credible in-service transportation conditions. It is these two aspects that are frequently the subject of debate.

8. Historically equipment that has survived the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity has been found to have very few problems in-service as a result of transportation vibrations. The extensive use of the test over very many years, with very few in-service problems, constitutes a substantial argument that the test is effective. With that said it is probably the case that the test has substantially driven military package designers into more expensive designs. Moreover, no quantitative evidence exists to prove the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity encompasses all credible in-service transportation conditions. The main purpose of this paper is to establish a base for such a quantitative comparison.

9. One reason for other test standards moving away from a similar generic sine sweep vibration test for transportation is a consequence of the difficulty of some packaged equipment to survive the test. It is the case that the existing “Transportation of Materiel” test is a difficult requirement which necessitates a quality of package design beyond that required for most commercial equipment. This is reflected in the failures that occur due to the “Transportation of Materiel” test, many of which can be attributable to inadequate package design (low damping, inadequate clearances etc). However, establishing difficult requirements is not without cost (in this case both financial and on the size of the packaged equipment) and should be avoided if possible. The SRETS work (Ref. 3) highlighted that package design for commercial equipment is really an “optimisation” between the increased cost of the package / logistics and the cost of equipment failure. Although for military applications the “equation” may be different, the general principle remains the same.

The Use of Damage Effect Parameters

10. The main reason for the lack of quantitative verification of the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity is because of the difficulty of doing so. The “Transportation of Materiel” test is a sine sweep, whilst, the measured conditions are based wholly, or in part, on analysis for random vibrations. Direct comparison of the two is fraught with difficulty and in many regards not realistic. For the purpose of this paper the different vibration environments are not compared directly, but rather in terms of their damage potential effects on the equipment. The damage affects addressed are peak acceleration response relating to internal loadings, (by means of Maximum Response Spectra - MRS) and fatigue (by means of Fatigue Damage Spectra - FDS). Additionally, consideration of maximum displacement is also possible to ensure motions do not exceed the available dynamic spatial envelope. A more extensive description of MRS and FDS is given in Annex A of this paper.

11. Maximum Response Spectra and Fatigue Damage Spectra are relatively recent techniques. The French Atomic Energy Authority published their work on MRS and FDS in the mid 1970’s and papers on the subject were published in France, the UK and the US. Unfortunately, because the method required a lot of computing and specialist computer programming, it was not extensively taken up at that time. However, in recent years the capabilities, have become readily available, to undertake the extensive computing required by MRS and FDS. In addition the use of MRD and FDS as a quantitative basis for setting test severities has been shown to be practicable. The advantage of using MRD and FDS as a quantitative basis for setting vibration test severities is that they can be used to set a traceable severity in terms of both vibration amplitude and test duration. This has been taken

up by the French MOD who have embedded the procedure into GAM EG 13. Moreover, the process has received substantial EU research funds and is now a commercially available product.

12. To alleviate the computational problems the originator of the method produced solutions specific to random vibration and sine sweeps. By making a number assumptions very significant improvements in computing time could be made. However, the necessary assumptions for random vibration and sine sweeps are different. In consequence, there was always a doubt that any differences identified may originate from the dissimilar assumptions rather than the environmental conditions. The advances in computing now allow MDS and FDS to be computed from an arbitrary waveforms in sensible timescales. With the ability to handle arbitrary waveform it is now feasible to compute MDS and FDS for both sine sweeps and random vibrations using the same method and using the same assumptions. Such computations are still quite lengthy but realistic pieces of data can now be processed in an hour or so rather than the several days required previously.

13. In order to establish potential damage both Maximum Response Spectra and Fatigue Damage Spectra adopt an approach of assuming the target equipment can be represented as a single degree of freedom dynamical system. Whilst, for equipment in general this is broadly valid, it is always prudent to consider the applicability for particular applications. This work only relates to equipment during packaged transportation. In almost all cases a package is intended to protect its contents from environmental conditions. Apart from very rugged equipment this usually includes vibration and shock. Practically a package protects its contents from vibration and shock by creating a single degree of freedom system with the equipment as the mass and the package supplying stiffness and damping. That is a package, by design, produces the conditions as assumed by MRS and FDS.

14. The computations, in this paper, of both Maximum Response Spectra and Fatigue Damage Spectra adopt a dynamic magnification (Q) of 10 (at the SDOF) resonance. The target for a well designed package would be for a Q of less than 5. However, in reality this is quite a difficult target to achieve and many packages are likely to have Q values in the range 5 to 10. When used for comparison purposes it has been shown that MRS & FDS result is not sensitive to the value of Q used in the computations. However, care needs to be taken if using the values directly for design purposes. In this case, care also needs to taken if the MRS results (from the vibration conditions) are compared with Shock Response Spectra values from transportation shocks.

15. A well designed package would normally have its fundamental natural frequency in the range 10 to 50 Hz. This is a practical range giving a realistic compromise between package size and degree of protection. A compromise is necessary because low fundamental natural frequencies results in good protection it also produces large displacements of the equipment. Conversely, high fundamental natural frequencies result in less protection against the applied shock and vibration environments. In practice a well designed package would have 6 primary natural frequencies one in each primary translational axis and one in each primary rotational axis. The frequency range of the "Transportation of Materiel" test is 5 to 350 Hz (for packages below 150 Kg) which supports the view that the test is intended for both good and bad packages.

Comparison of Transportation Damage Effects

16. The original intent of this work was to compare the effects of actual transportation conditions with the Def Stan 00-35 Part 3 "Transportation of Materiel" vibration test severity. However, the extensive use of actual transportation environmental conditions involves a considerable amount of computation. To reduce the amount of computation required, in the first instance, comparison was made with the various test severities set out in Def Stan 00-35 Part 5 for specific modes of transport. Comparison only with test severities is not necessarily a conclusive indication as to the validity of the "Transportation of Materiel" test. This is because the Part 5 tests have their own (and widely different) test margins and some are of doubtful applicability. Consequently, whilst, the comparison is initially against the Part 5 tests, when these are indicated as producing damage similar to that of the "Transportation of Materiel" test further consideration is with actual conditions. As a technical aside;

the test severities were limited to a crest factor of 3 (to replicate that used when testing), however, no practical crest factor limit was imposed on the actual conditions.

17. The initial intent was to group the comparison into those occurring up to forward depot (3rd to 2nd line transport) and those occurring beyond the forward depot (2nd to 1st line transportation). One advantage of this strategy is that transportation up to the forward depot adopts essentially commercial means of transport and are, hence, directly comparable with the severities of commercial environmental testing standards. This is not the case for transport beyond the forward depot which includes mostly military modes of transport and military vehicle types which are unlikely to be encountered in normal commercial transport. Initial perusal of the results indicated that for conditions arising from transportation beyond the forward depot, the results needed be addressed separately for the sake of clarity.

18. In addition to both Maximum Response Spectra and Fatigue Damage Spectra the comparison presented in the following paragraphs also includes consideration of Displacement Maximum Response Spectra (DMRS). This was included, somewhat belatedly, in the work because it seemed relevant to do so. Consideration of a number of failures of packaged equipment from the "Transportation of Materiel" test suggest that excessive equipment displacement is a consideration. Such failures occur because of either impacting of the equipment with the inside of the package or due to the non-linear characteristics of the package furniture. Ideally the work should have considered relative displacement (representing that between the package and the equipment). Unfortunately, before it was decided to include Displacement Maximum Response Spectra a significant number of computer runs had been completed and relative displacement could not readily be computed retrospectively. However, computation of absolute displacement was possible (from the MRS values) and it is that which is included here.

Commercial Transportation / Transportation to Forward Depot

19. For the purpose of this paper "Transportation to Forward Depot" includes transportation by wheeled vehicles on metalled roads as well as transport by sea, rail and large fixed wing jet aircraft. All of these are effectively commercial transportation. Figures 1 to 3 compare the Def Stan 00-35 Part 5 test severities with the Def Stan 00-35 Part 3 "Transportation of Materiel" vibration test severity, for MRS, DMRS and FDS respectively. As well as the Def Stan 00-35 Part 5 test severities also included in these figures are the sea transport severities from BS 60945 and the sea transport severity from Mil Std 810. These alternative sea transport severities are included because of doubt concerning the validity of the Def Stan 00-35 Part 5 severity for sea transportation. Also the Def Stan 00-35 Part 5 severity required pre-knowledge of the dynamic characteristics of the packaged equipment.

20. The figures clearly indicate that of the Def Stan 00-35 Part 3 "Transportation of Materiel" vibration test severity easily encompasses the various Def Stan 00-35 Pt 5 test severities. At lower frequencies (less than 20 Hz) the exceedances are pronounced (around 5 on maximum acceleration and displacement and around 1000 on transportation duration). Also the road transportation test severity is clearly the dominant condition and could, for practical purposes, be used to encompass all the other commercial transportation conditions. This is essentially in agreement with the experience of designers of packages and equipment intended purely for commercial transport. Their experience indicates the Def Stan 00-35 Part 3 "Transportation of Materiel" vibration test severity is a generally an overtest for commercial equipment, particularly at low frequencies. Commercial experience also indicates that road transportation is the most damaging commercial transportation environment.

21. The road transportation test severity of Def Stan 00-35 Pt 5 is broadly consistent with the equivalent tests in other defence standards (Mil Std 810, STANAG 4370 and GAM EG 13). Figures 4 to 9 compare the environmental severities set out in the commercial standard BS EN (also IEC) 60731-3-2 for transportation vibration with both the various Def Stan severities. The IEC standard has three categories (although the vibration severities for the first two are identical) and describes the

environment in terms of both sine and random vibration. It is of note that damage potentials of the sine and random severities are significantly different. The damage potential of the higher (category 2M3) sine severity is very similar to the Def Stan sine test severity, whilst, the higher random severity exceeds the Def Stan 00-35 Pt 5 road transport severity. Opinion exists that the lower level IEC random severities (category 2M1 and 2M2) adequately encompass actual conditions. Work to verify this is ongoing.

22. A recent EU funded SRETS study has indicated that actual conditions on modern commercial vehicles on European public roads are markedly lower than indicated by defence standards. That work has now been published (ref. 3) and is forming the basis for a revision of various international standards. However, that work also indicated that large variations exist on measurements taken from wheeled vehicles even from similar vehicles on the same route carrying the same payload. This variation is attributed almost entirely due to the way the vehicle is driven (many of the SRETS measurements were made covertly).

23. A recent comparison exercise for IEC 60721 by Working Group 15 of IEC Technical Committee No 104 suggests that the Def Stan 00-35 Pt 5 Jet Air transport severities are reasonable for a range of aircraft. As already intimated some doubt exists as to the applicability of the Def Stan 00-35 Pt 5 test severity for sea transport. As can be seen significant variations exist between the three tests considered. In this case the commercial severity from BS EN 60945 appears to largely encompass the other two military severities and requires no knowledge of the dynamic characteristics of the packaged equipment.

24. In summary the results suggest that if equipment is to be subject only to transportation directly equivalent to commercial transportation then the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity is probably excessive and resulting in the over design (and oversize) of packages particularly as a result of the low frequency displacement requirements.

Military Transportation / Transportation Beyond the Forward Depot

24. For the purpose of this paper “Transportation Beyond the Forward Depot” includes transportation by wheeled vehicles on degraded roads and off-road, transportation by tracked vehicles, transportation by air including rotary wing aircraft and propeller aircraft. Few if any of these have commercial equivalents.

Rotary Wing Air Transportation

25. Of all the transportation modes that can occur beyond the forward depot transportation by helicopters is the one which seemed likely to generate the most critical condition for packaged equipment. This is because the dominant excitations from helicopters are at blade passing frequencies (typically 11 to 25 Hz) which occur at or below the frequencies at many packages offer protection to their content. Figures 10 to 12 compare the Def Stan 00-35 Part 5 test severity for transportation by helicopter, against the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test. Also included in these figures are actual values for transportation by Chinook, Lynx and Seaking. All the actual conditions are based upon worst case measurements at the aircraft cargo floor. In this case worst case conditions occur during transitory manoeuvres rather than steady flight and are all in the vertical axis. For Chinook sufficient information was available to create a realistic flight sortie from which a realistic test duration could be derived for use in the FDS calculations. Insufficient information for the other two aircraft necessitated the assumption of a 2 hour test (as per the Def Stan 00-35 test duration).

26. In order to establish the Def Stan 00-35 Part 5 test severity for transportation within helicopters it is necessary to identify the specific aircraft. This is necessary to permit the appropriate choice of rotor blade passing frequency. The test incorporates two sine (or narrow band) components centred at 1st and 2nd blade passing frequencies for the specific helicopter superimposed onto a wide

band random background. The severities for the vertical and lateral axes are identical but the two sine (or narrow band) components for the fore/aft severities are lower. For the purpose of this work the Def Stan 00-35 Part 5 test severity was derived assuming transportation in Chinook (as it has one of the lowest blade passing frequencies). For guidance the range of other possible blade passing frequencies for potential UK transport helicopters are indicated on the figures. Technical note; Def Stan 00-35 permits the use of either sine or narrow band components, for the purpose of these calculations sine was assumed as it gives (marginally) the worst case MRS values.

27. As can be seen from the MRS and DMRS figures, the 1st and 2nd blade passing components produce very similar values to that of the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity. Indeed the 2nd blade passing component marginally exceeds the “Transportation of Materiel” level. The FDS figure indicates that, at the 1st and 2nd blade passing frequencies, around 100 times more fatigue damage is induced by the helicopter specific test as would be by the “Transportation of Materiel” test. However, this would only be the case for packaged equipment with a natural frequency which matched almost exactly with the 1st or 2nd blade passing frequencies. At all other frequencies the “Transportation of Materiel” test produces markedly more severe conditions, against all three criteria. When actual aircraft conditions are addressed exceedances are not indicated against any criteria at any frequency. This suggests that the indicated exceedances of the Def Stan 00-35 Pt 5 test are well within the test margin. This is not that surprising as the margin on the Def Stan 00-35 Pt 5 helicopter transportation test has for some time been considered excessive.

28. Two incidental points are apparent in the results which are worthy of note. The first arises from the observation that the greatest exceedances occur at the 2nd blade passing frequency. This is because the test amplitude at both 1st and 2nd blade passing frequencies are identical. However, in reality the 2nd blade passing frequency is not as severe as that at the 1st blade passing frequency (especially at the most severe flight conditions). In short the main exceedances may be as a result of a overly severe test severity at the 2nd blade passing frequency.

29. The second point of note is that the most severe damage potential at either blade passing component occurs over a very narrow range of frequencies and is far less than the potential variations due to different helicopters. This would also have been the case had a lower Q value been used in the calculations. In short no single test for helicopter transportation, derived from the Def Stan 00-35 Pt 5 procedure, can be used to encompass the effects of all aircraft types that may be used by the UK military. Moreover, the only way to identify which aircraft will induce the most severe damage requires pre-knowledge of the dynamic characteristics of the packaged equipment. Looked at another way the sometimes used approach of augmenting the “Transportation of Materiel” with an additional helicopter test cannot, without knowledge of the dynamic characteristics of the packaged equipment, be assumed to inducing the worst case conditions.

Fixed Wing Propeller Air Transportation

30. Severe vibration conditions have long been known to occur in military fixed wing propeller aircraft. However, the dominant blade passing excitation frequencies are usually greater than the fundamental natural frequencies of many packaged equipments. As such the package is able to offer some protection, to the equipment, from the applied vibrations. Figures 13 to 15 compare the Def Stan 00-35 Part 5 test severity for transportation by fixed wing propeller aircraft against the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test. Also included in these figures are actual values for transportation by the Hercules (C130) aircraft as well as the aircraft manufacturers design levels for the C130J. All the actual conditions are based upon worst case measurements at the aircraft cargo floor. In this case worst case conditions occur during take-off / landing rather than steady flight and are all in the vertical axis. In both cases sufficient information was available to create a realistic flight sortie from which test duration could be derived for use in the FDS calculations.

31. In order to establish the Def Stan 00-35 Part 5 test severity for transportation within propeller aircraft it is necessary to identify the specific aircraft. This is to permit the appropriate choice at

propeller blade passing frequency. The test incorporates three sine (or narrow band) components centred at 1st, 2nd and 3rd blade passing frequencies superimposed onto a wide band random background. The severities for the vertical and lateral axes are identical but the blade passing components for the fore/aft severities are lower in amplitude. For the purpose of this work the Def Stan 00-35 Part 5 test severity was derived assuming transportation in C130. For guidance the range of other possible blade passing frequencies for potential transport aircraft is indicated on the figures. In practice the different values for the C130 and the C130J encompass most other potential transport aircraft.

32. The figures show that the MRS and DMRS values at the 1st , 2nd and 3rd blade passing components produce similar or higher values to that of the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity. Consideration of actual C130 conditions indicates the 1st blade passing component as just less than the “Transportation of Materiel” value and significantly lower at the that the 2nd and 3rd blade passing frequencies.

33. The FDS figure indicates that, at the 1st , 2nd and 3rd blade passing frequencies, over 100 times more fatigue damage is induced by the aircraft specific test as would be by the “Transportation of Materiel” test. However, this would only be the case for packaged equipment with a natural frequency centred on the 1st , 2nd or 3rd blade passing frequencies At all other frequencies the “Transportation of Materiel” test produces similar damage. In this case fatigue damage exceedances also occur when actual aircraft conditions are considered. As was also the case for helicopter transportation the results indicate that the most severe damage occurs only over a very narrow range of frequencies and is far less than the potential variations due to different aircraft. Again implying that, without knowledge of the dynamic characteristics of the packaged equipment, no single propeller transportation test, derived from Def Stan 00-35 Pt 5 procedure, can be assumed to encompass all types of aircraft that may be used by the UK military (in particular a test derived for the C130 will not encompass the conditions of the C130J).

Degraded Road and Off Road Wheeled Vehicle Transportation

34. The Def Stan 00-35 Pt 5 test severity for wheeled transportation beyond the forward depot is intended for degraded and off road transportation. However, the vibration (and shock) severities are simply the normal road transport test severity doubled in amplitude. Figures 16 to 18 compare the Def Stan 00-35 Part 5 test severity for degraded and off road transportation beyond the forward depot, against the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity. Also included in these figures are actual values for degraded and off road transportation in the back of a Landrover, a 10 tonne Armament Support Vehicle (ASV), degraded road transport in a Ford Transit and a 38 tonne Renault Magnum. Also included are degraded and off road conditions in a BV206. Although the BV206 is a tracked vehicle it is commonly used for equipment transportation and, because of its rubber tracks, produces conditions more consistent with wheeled vehicles. All the actual conditions are based upon worst case measurements at the cargo floor and, excepting the ASV data, were obtained from test tracks. All worst case conditions occur in the vehicle vertical axis. As different information was available for each of the vehicles, it was not practical to create a consistent transport mission from which a test duration for use in the FDS calculations could be developed. For this reason a 2 hour test was assumed (as per the Def Stan 00-35 Part 5 test severity).

35. The MRS and DMRS figures indicate that the Def Stan 00-35 Pt 5 test severity for degraded and off road wheeled transportation exceeds the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity by around 50% but only at frequencies above 30 Hz. However, the FDS indicated that the “Transportation of Materiel” vibration test severity produces greater fatigue damage than the Part 5 test at all frequencies (i.e. a sine sweep generates greater fatigue damage than a random test). The figures also indicate a significant difference between the Part 5 test and actual measurements in the various vehicles. The ASV information is particularly interesting as it contains a significant low frequency contribution from the vehicle suspension (around 3 Hz). This does not show significantly on the MRS but (due to the large displacements) is very marked on the DMRS and FDS.

36. The characteristics of the ASV data are consistent with a significant amount of observed degraded road and cross country measurements. That is the low frequency vibration responses of the vehicle suspension dominates the spectra with the suspension mode acting as a classic 2 pole filter suppressing responses at higher frequencies. Only at relatively high frequencies (200 Hz plus) does this trend cease. Whilst, this characteristic is not reflected in the Def Stan 00-35 Pt 5 test severity, it is reflected in the Mil Std 810 severities for equivalent conditions. Figures 19 to 21 compare the Def Stan 00-35 Pt 3 “Transportation of Materiel” vibration test severity and the Part 5 severity with the Mil Std 810 severity. These figures illustrate very clearly the marked difference between the Part 5 characteristic and that of the Mil Std severities.

37. It is not the intent of this paper to propose the adoption of the Mil Std 810 severity, if for no other reason they cannot be achieved in practice. However, the characteristic does seem to better reflect actual severe off-road conditions. The difference is quite important for package design and has significant implications to the purpose of this paper. Essentially, the characteristics of the Mil Std type off-road wheeled transportation seems to be the only condition that justifies the very low frequencies of the “Transportation of Materiel” test. If the low frequency does not really exist then appropriately modifying the “Transportation of Materiel” could significant ease package design (and size). Additionally the current “bounce” test could also be argued as unnecessary.

Tracked Vehicle Transportation

38. Although transportation by tracked vehicle is only likely to be encountered by some equipment, it is included here for completeness. The Def Stan 00-35 Pt 5 test severity for transportation by tracked vehicles comprises a fairly severe broad band random vibration background with three superimposed significant swept sine (or narrow band) components. The swept sine components are harmonically related. Figures 22 to 24 compare the Def Stan 00-35 Part 5 test severity for tracked vehicle transportation, against the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity. Also included in the figures are actual information from the Warrior APC as well as from the FV432 and BV206 vehicles. All the actual conditions are based upon worst case measurements at the vehicle floor and were obtained from test tracks. All the worst conditions occur in the vehicle vertical axis. Insufficient information was available from any of the vehicles to create a realistic test duration for use in the FDS calculations, as such a 2 hour test was assumed (as per the Def Stan 00-35 Part 5 test severity).

39. Excepting for the BV206 (discussed previously), both the Def Stan 00-35 Pt 5 severities and the actual conditions exceed the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity above around 20 Hz. The Pt 5 and actual vehicle information all relate to conditions of severe vehicle usage. Whether such conditions would occur during transportation is debatable.

Discussion

40. The results indicate that whilst the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity encompasses the potential damage for the majority of credible military transportation conditions it does not encompass all effects. In order to address further the capability and shortfalls of the existing test the various Def Stan 00-35 Part 5 test severities for transportation are summarised in Figures 25 to 27. Similarly Figures 28 to 30 summarise all the actual conditions. Neither of the above comparisons includes tracked vehicles (excepting BV206) as to do was thought to significantly bias any debate towards a mode of transport only experienced by a limited range of packaged equipment.

41. As indicated earlier, the use of severities similar to the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity is now unusual for purely commercial equipment. The results presented in this paper suggest that if equipment is restricted to transportation directly equivalent to commercial transportation then the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity has an overly severe damage potential. As such it’s use is probably excessive and resulting in

over designed and oversize packages. A more appropriate severity would be the on-road wheeled vehicle severity of Def Stan 00-35 Pt 5.

42. The above notwithstanding, the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity is intended, and mainly used, for military transportation. Moreover, it should be no great surprise that military transportation, particularly beyond the forward depot, is indicated as having the potential to produce far more severe damage than commercial transportation. When consideration of military transportation conditions is included then the Def Stan 00-35 Part 3 “Transportation of Materiel” vibration test severity seems reasonably adequate (or more accurately it is not shown to be grossly inadequate).

43. An interesting observation from the results is that almost all the conditions producing the greatest damage potential arise from sine components or sine like narrow band components. This is interesting because it challenges a frequently voiced criticism of the “Transportation of Materiel” severity is that it is a sine sweep and does not replicate the random vibrations of actual conditions. As can be seen from the results it is mostly the sine components or sine like narrow band components that produce the most damaging conditions. An implication is that maybe any replacement for the “Transportation of Materiel” severity should be a sine dwell test rather than random vibration test.

44. Another significant (as less tongue in cheek) observation from the results is that no single Def Stan 00-35 Pt 5 test encompasses the worst case damage potential for all credible packaged equipments. Moreover, no single environmental condition has this potential either. As such there is no obvious single existing test or transportation condition that that can be legitimately used to replace the existing generic “Transportation of Materiel” severity.

45. When all three damage criteria are considered the results would, superficially, suggest then at least three separate tests would be required to replace the “Transportation of Materiel” that is if no knowledge of the packaged equipment is to be assumed. Superficially the three modes of transport that could be used to encompass all others are wheeled vehicles beyond forward depot, helicopter transportation and propeller aircraft transportation. Additionally tracked vehicle transportation would need to be included if that was a possible mode of transport. Unfortunately, when the results are considered in detail, all three of these tests have problems or a question mark against them.

46. The problem with two of the tests is that they are for modes of transport (helicopter and propeller aircraft) which are vehicle type specific. The results indicate that a single vehicle type does not encompass the potential damage that may occur if other types of helicopter or propeller aircraft are used for transportation purposes. If it is assumed that in-service any (current or future) aircraft type may be used then the only way to identify the most “damaging” aircraft types would be to have knowledge of the dynamic characteristics of the packaged equipment. The results would also suggest that, without such knowledge of the dynamic characteristics of the packaged equipment, the sometimes used approach of augmenting the “Transportation of Materiel” with an additional of helicopter or propeller aircraft test is not an appropriate or valid approach.

47. The degraded and off road wheeled vehicle vibration test in Def Stan 00-35 Pt 5 is significantly different in characteristic, for off-road and degraded conditions, to those observed and those in some other specifications. Moreover, it is the only condition that seems to justify the very low frequencies of the “Transportation of Materiel” test. The differences between Pt 5 and some other specifications is most marked at both low frequency and in the 20 to 60 Hz region. Both of these regions are of concern in package design (affecting cost and size).

Conclusions

48. Superficially the work presented in this paper seems to have identified more problems than it resolved. This is because the work has identified a number of problems with the current Def

Stan 00-35 Pt 5 tests which need to be resolved. However, having been identified they all seem solvable.

49. So far this paper has evaded the question as to whether a single test to encompass all (or most) forms of transport is actually needed. From the viewpoint of the author (i.e. an equipment supplier) such a test appears to have significant cost advantages provided packaged equipment can survive it. It also seems highly desirable and cost effective, from the viewpoint of the service user, in that they do not having to worry about equipment transportation limitation either now or in the future (when new transport vehicles are introduced). Again provided the test is not excessively pushing up equipment or logistic costs.

50. The work indicates that the current “Transportation of Materiel” sine sweep test does seem to sensibly encompass, or be equal to, most forms of military transportation. Whilst, some forms of transportation produces, in the worst case, damage conditions in excess of the “Transportation of Materiel” sine sweep test, these are not primary modes of transport. One concern exists with the current test as to the validity of the low frequency components and that revolves around the resolution of the type of spectra induced by degraded and off-road wheeled vehicle transportation.

51. No single replacement for the “Transportation of Materiel” sine sweep test could be identified amongst the existing Def Stan 00-35 Part 5 tests. Indeed it would take 3 or 4 of the existing tests to replace the “Transportation of Materiel” sine sweep test and even then it would necessitate knowledge of the dynamic characteristics of the packaged equipment.

References

1. Environmental Handbook for Defence Materiel, Def Stan 00-35, Issue 3 May 1999.

2. BS EN 60721-3-2 Classification of Environmental Conditions, Part 3, Section 2 Transportation.

3. Final Report - SRETS (Source Reduction by European Testing Schedules), Contract No SMT4-CT95-2005, editor; Dr U Braunmiller Fraunhofer ICT.

4. Vibration and Shock of Equipment Carried in Fixed Wing Jet Aircraft, TC104/WG15(Report)/01, 2000-08

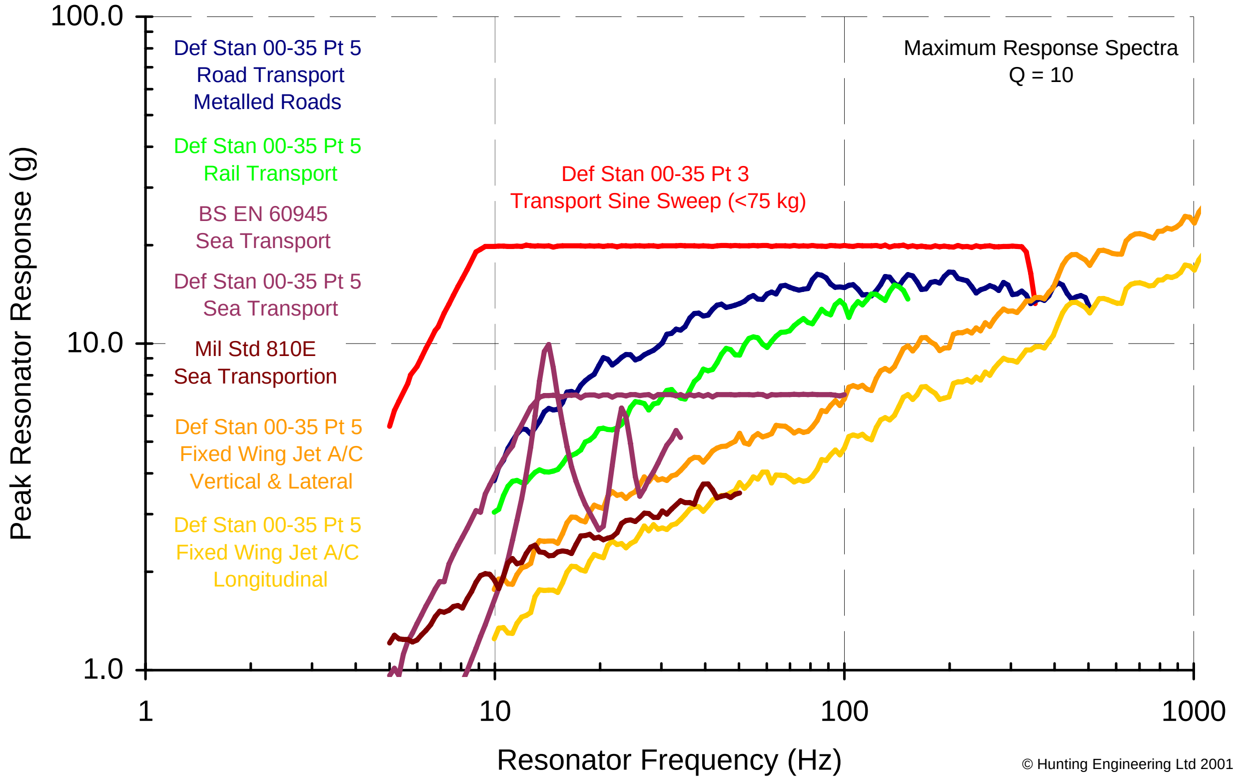

Figure 1 Comparison of Def Stan 00-35 Tests Typical 3rd to 2nd Line Transportation - MRS

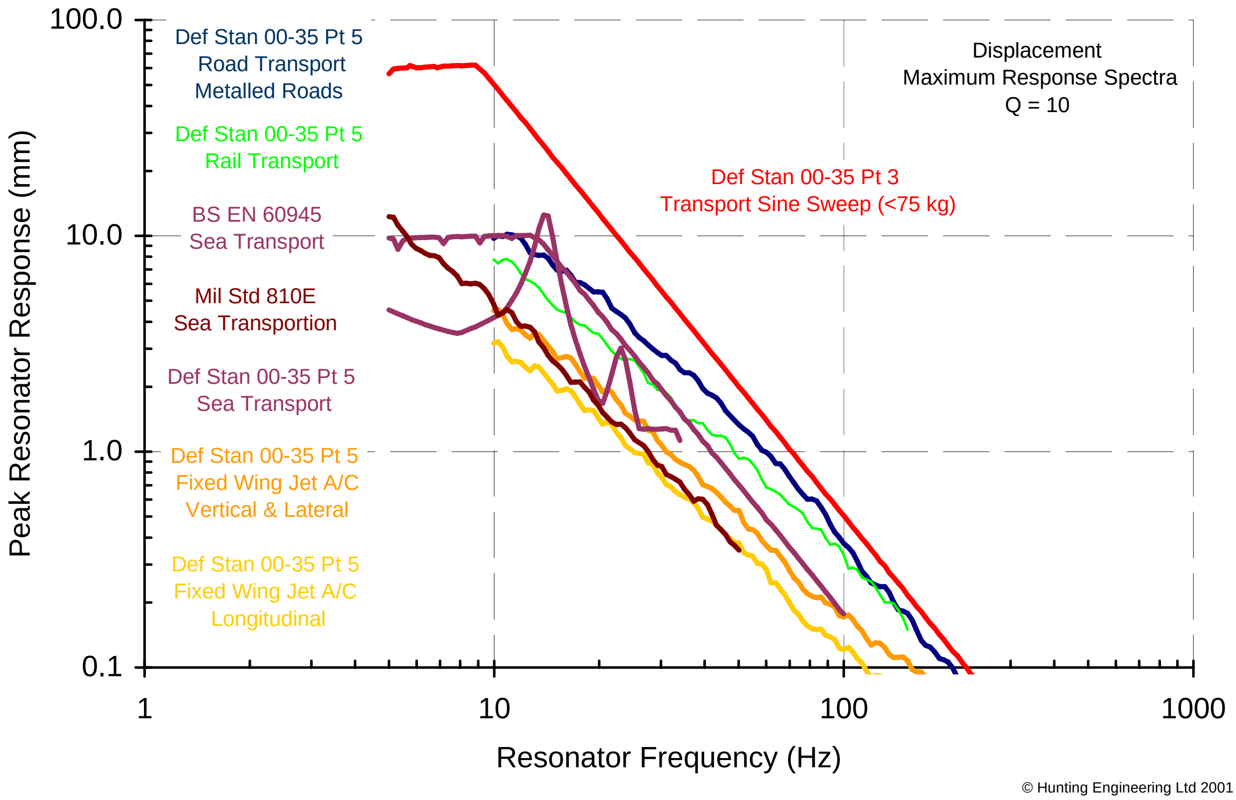

Figure 2 Comparison of Def Stan 00-35 Tests Typical 3rd to 2nd Line Transportation - DMRS

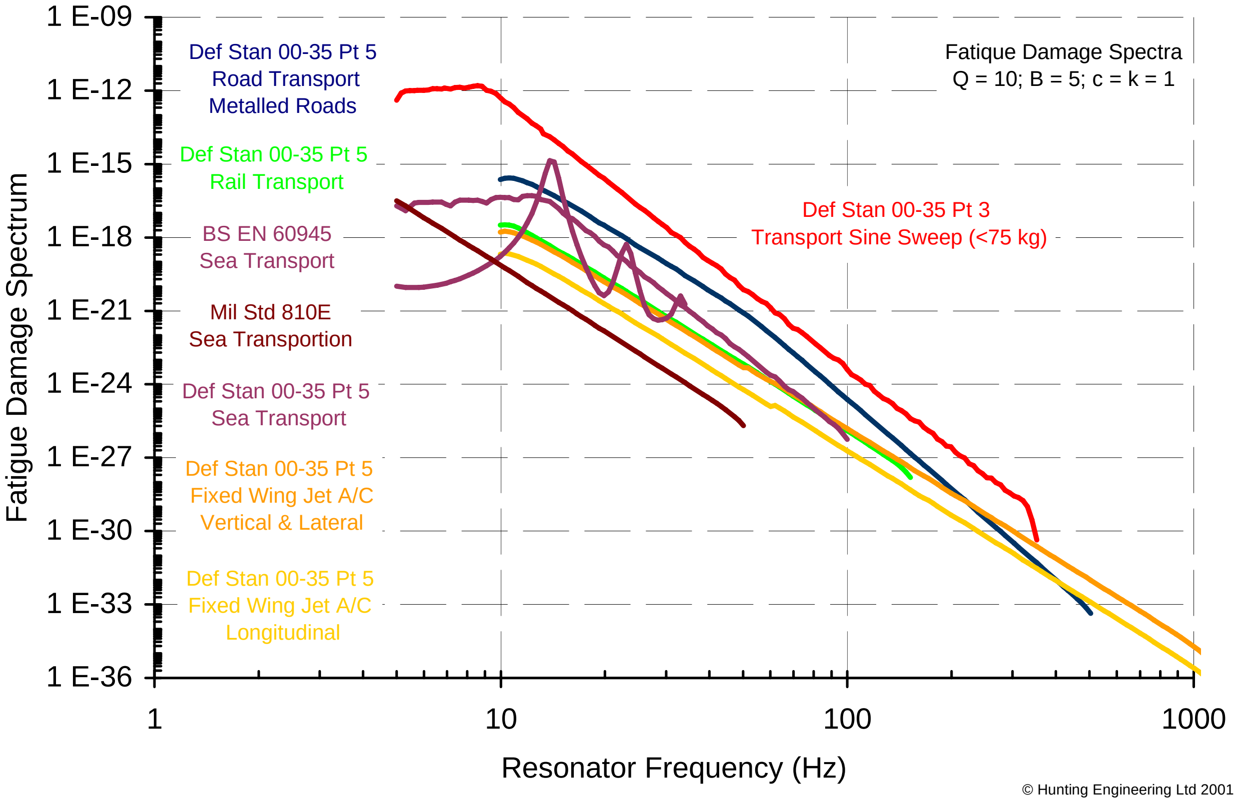

Figure 3 Comparison of Def Stan 00-35 Tests Typical 3rd to 2nd Line Transportation - FDS

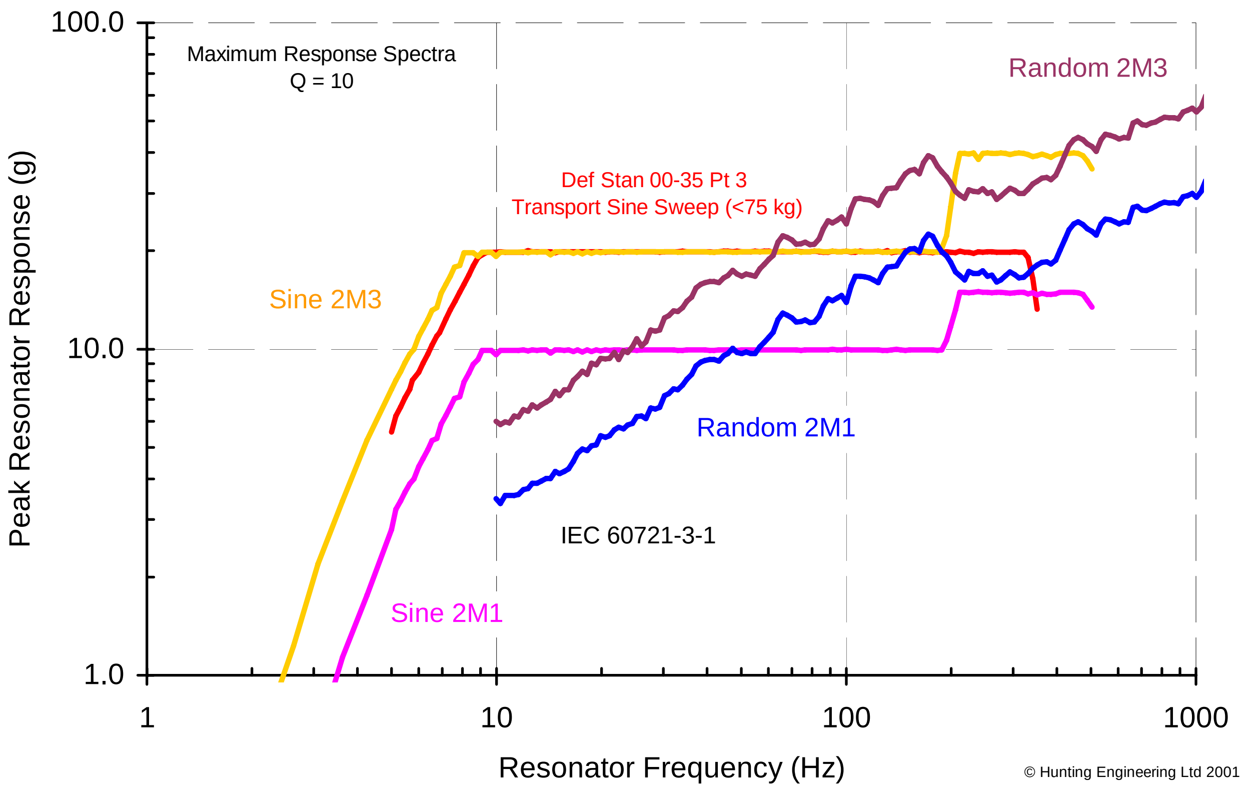

Figure 4 Comparison of Def Stan 00-35 Test and IEC 60721-3-2 Severities - MRS

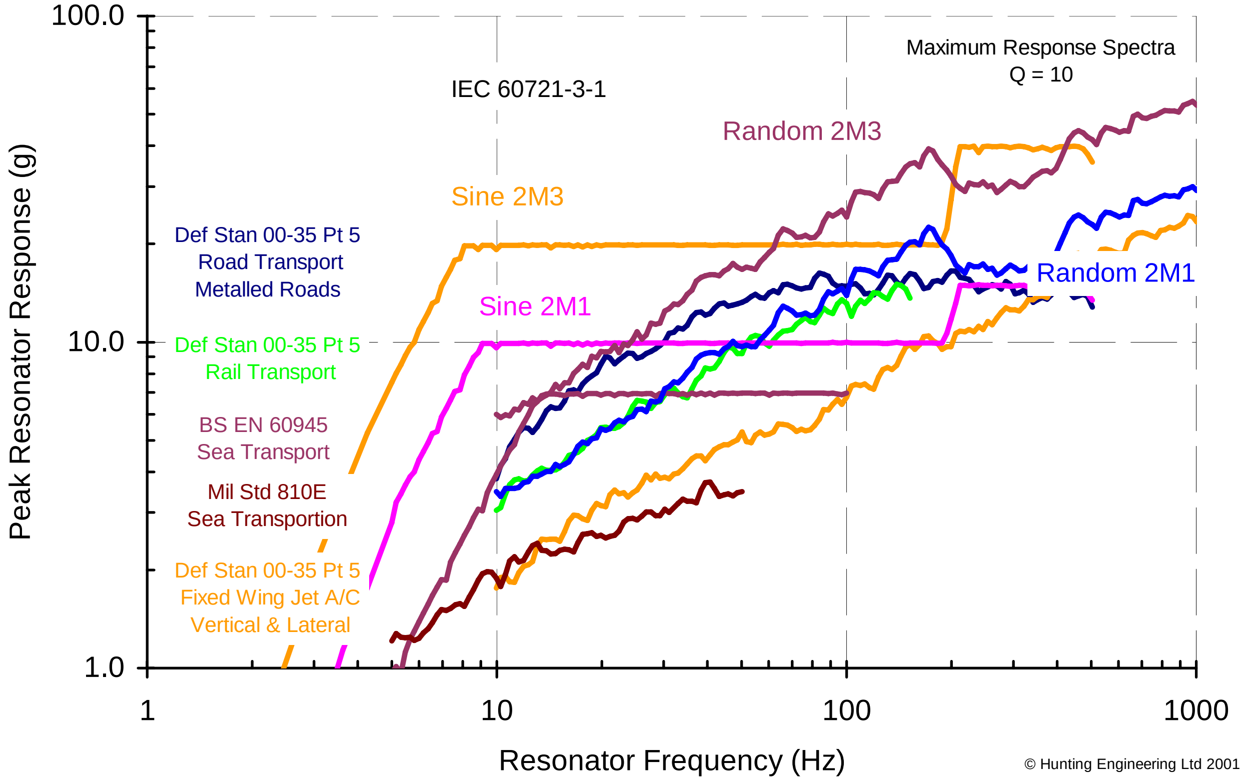

Figure 5 Comparison of IEC 607213-2 Severities with Specific Tests - MRS

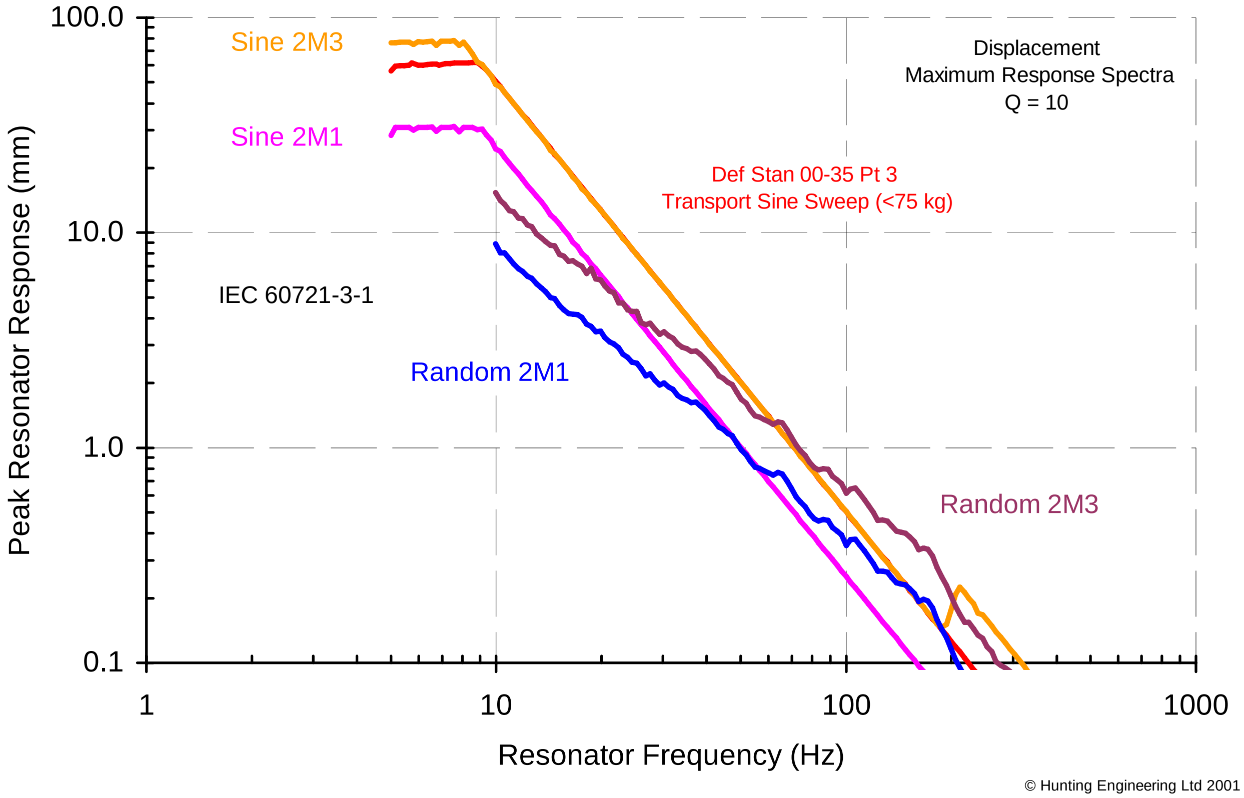

Figure 6 Comparison of Def Stan 00-35 Test and IEC 60721-3-2 Severities - DMRS

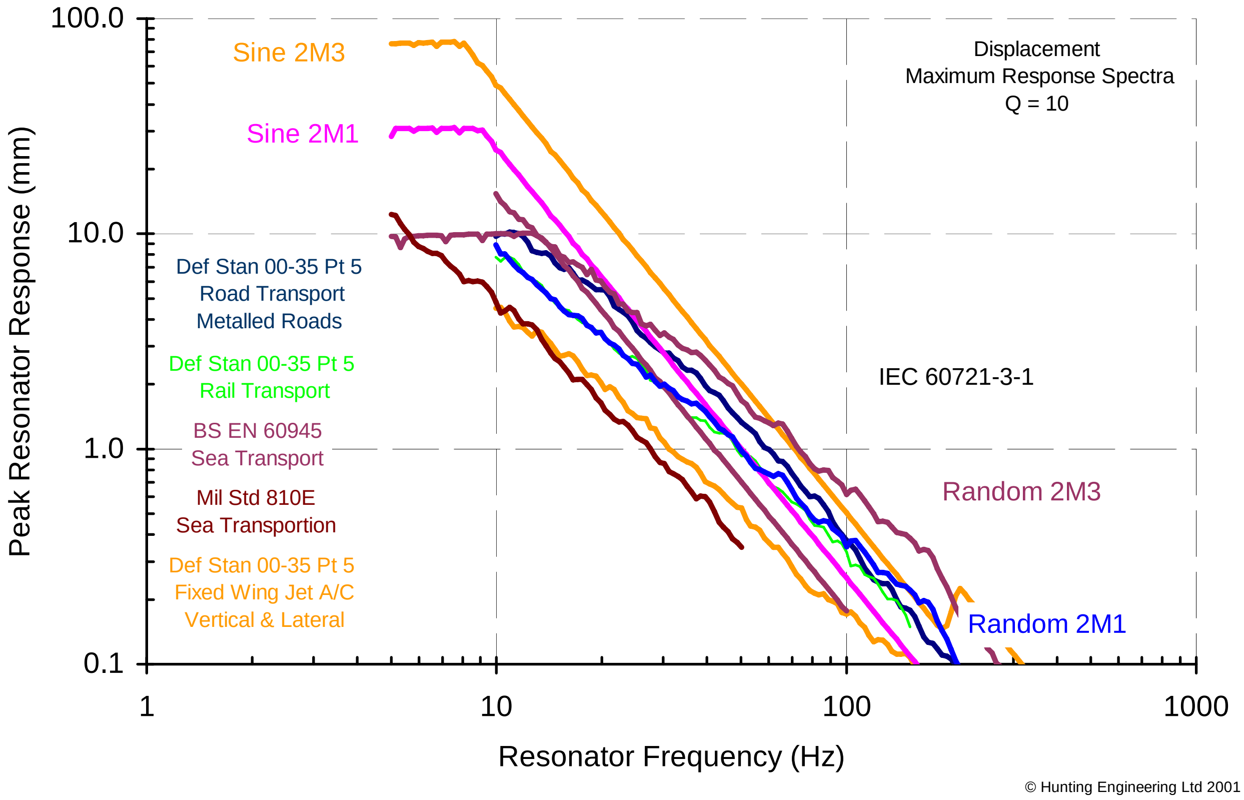

Figure 7 Comparison of IEC 607213-2 Severities with Specific Tests - DMRS

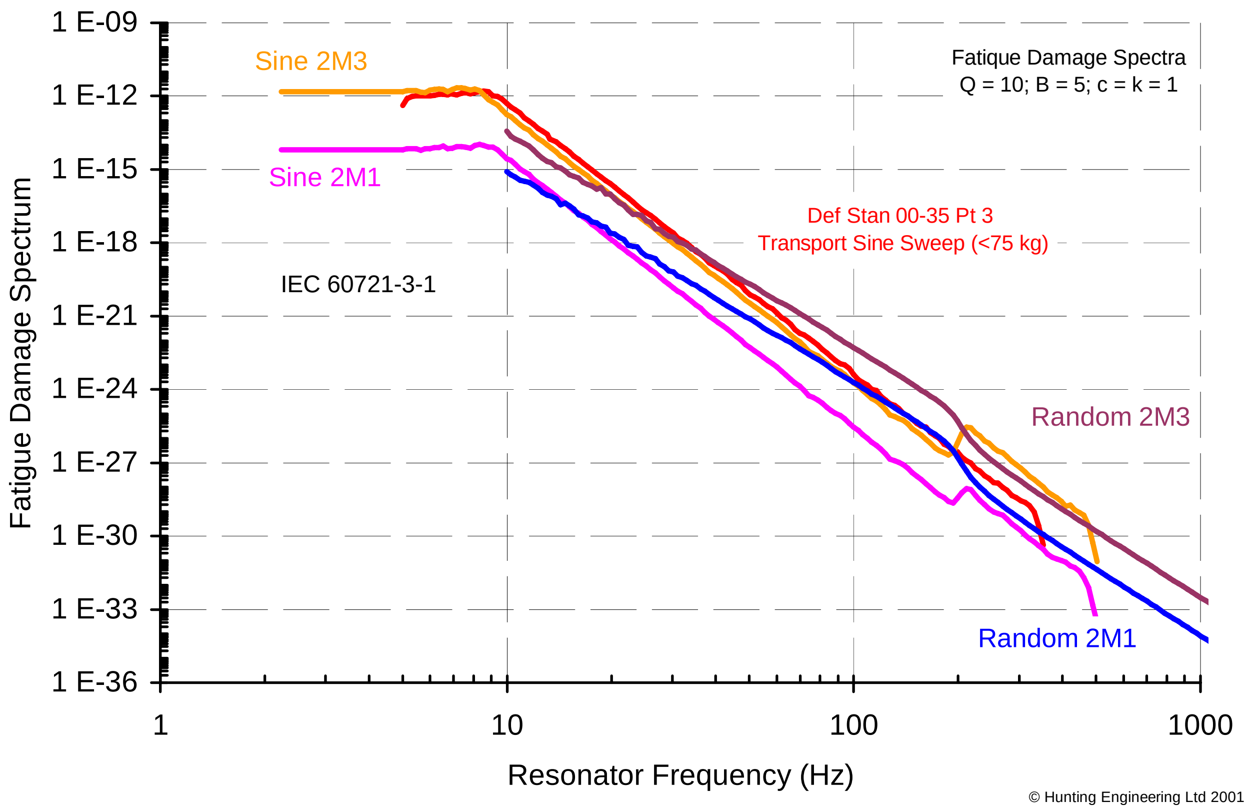

Figure 8 Comparison of Def Stan 00-35 Test and IEC 60721-3-2 Severities - FDS

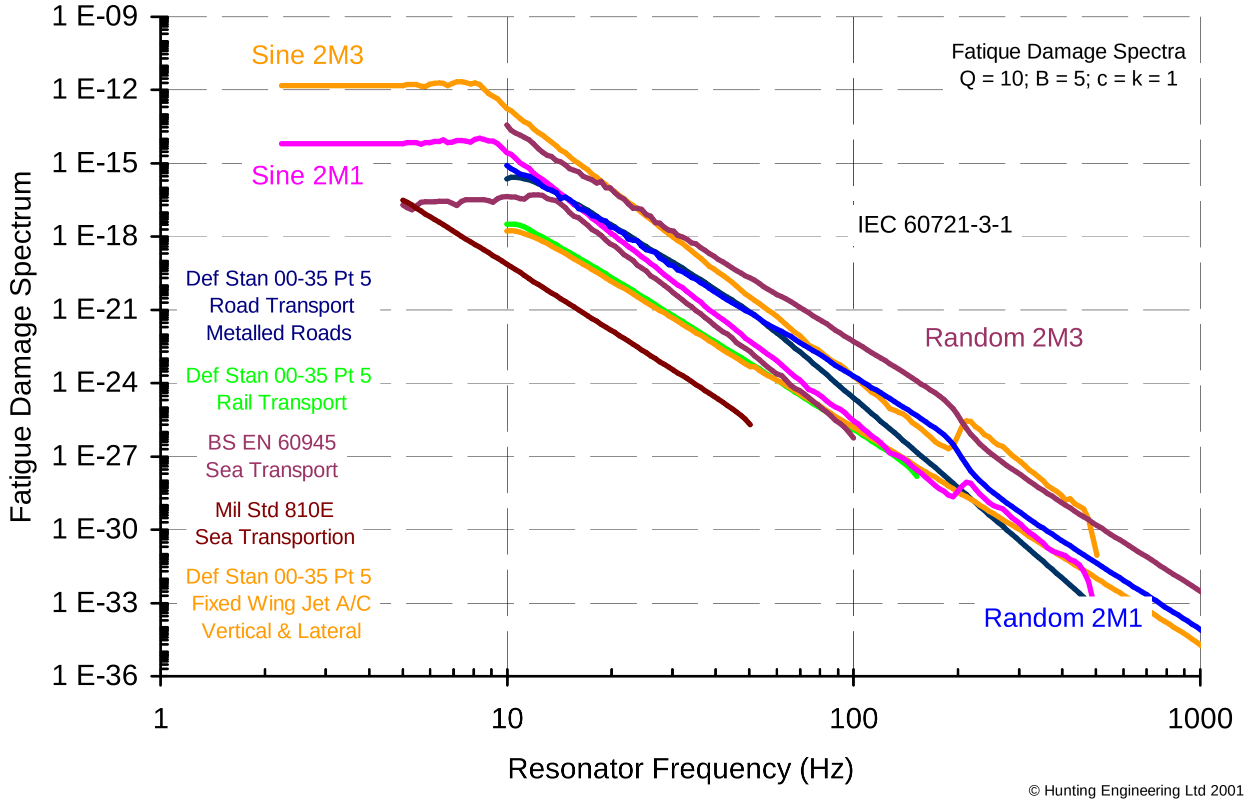

Figure 9 Comparison of IEC 607213-2 Severities with Specific Tests - FDS

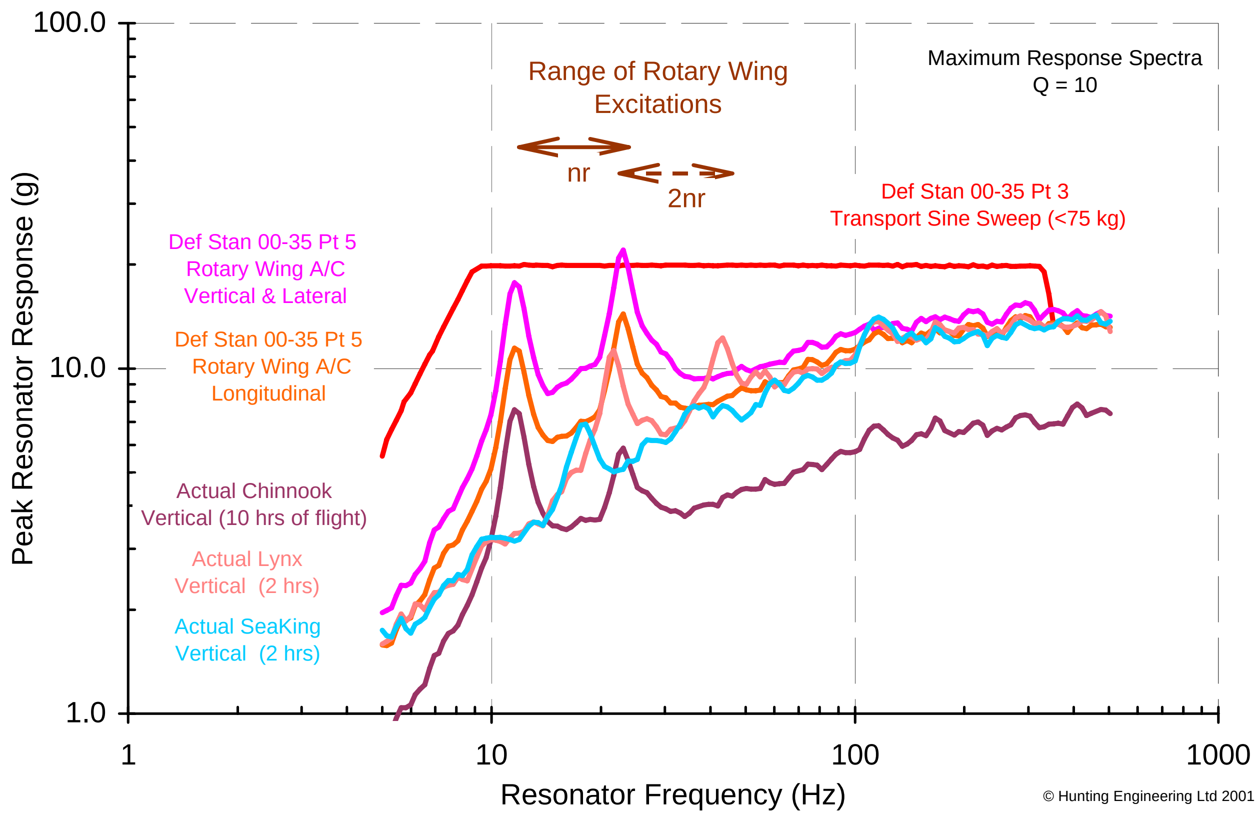

Figure 10 Comparison of Def Stan 00-35 Tests Rotary Wing Air Transportation - MRS

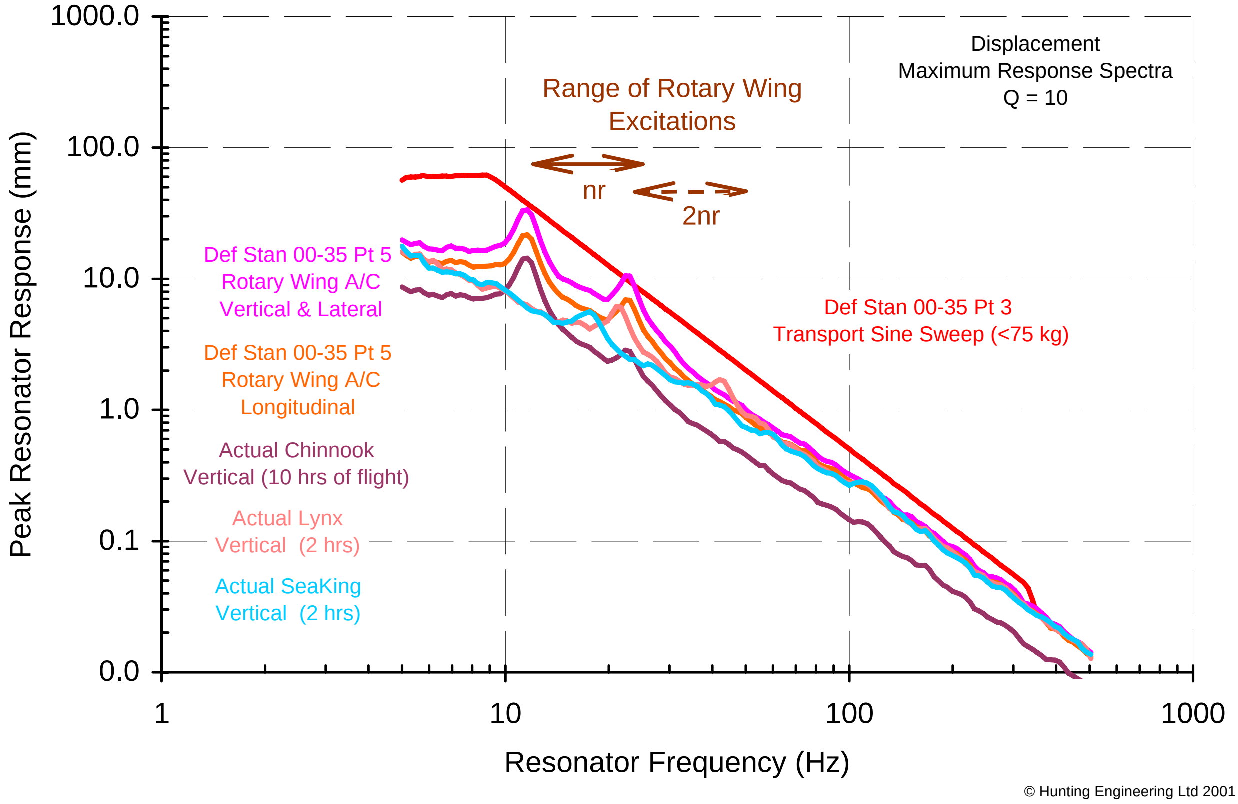

Figure 11 Comparison of Def Stan 00-35 Tests Rotary Wing Air Transportation - DMRS

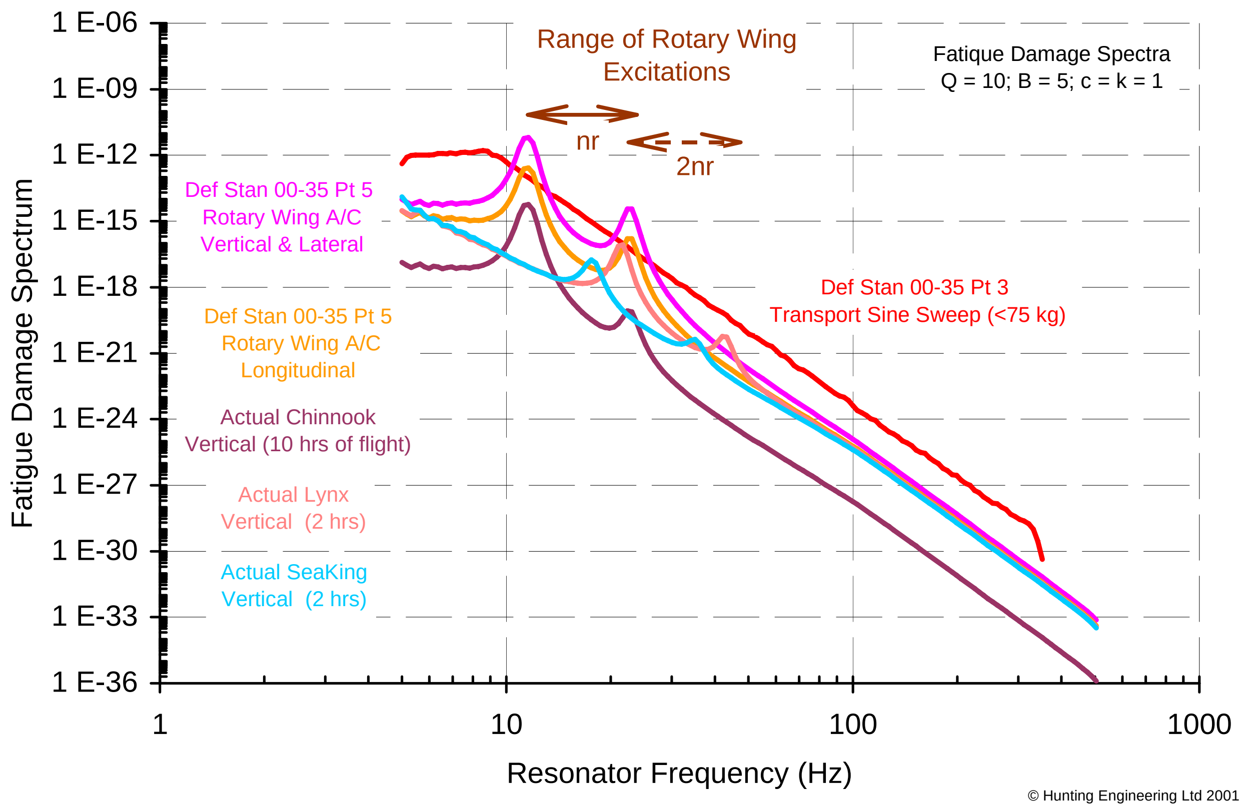

Figure 12 Comparison of Def Stan 00-35 Tests Rotary Wing Air Transportation - FDS

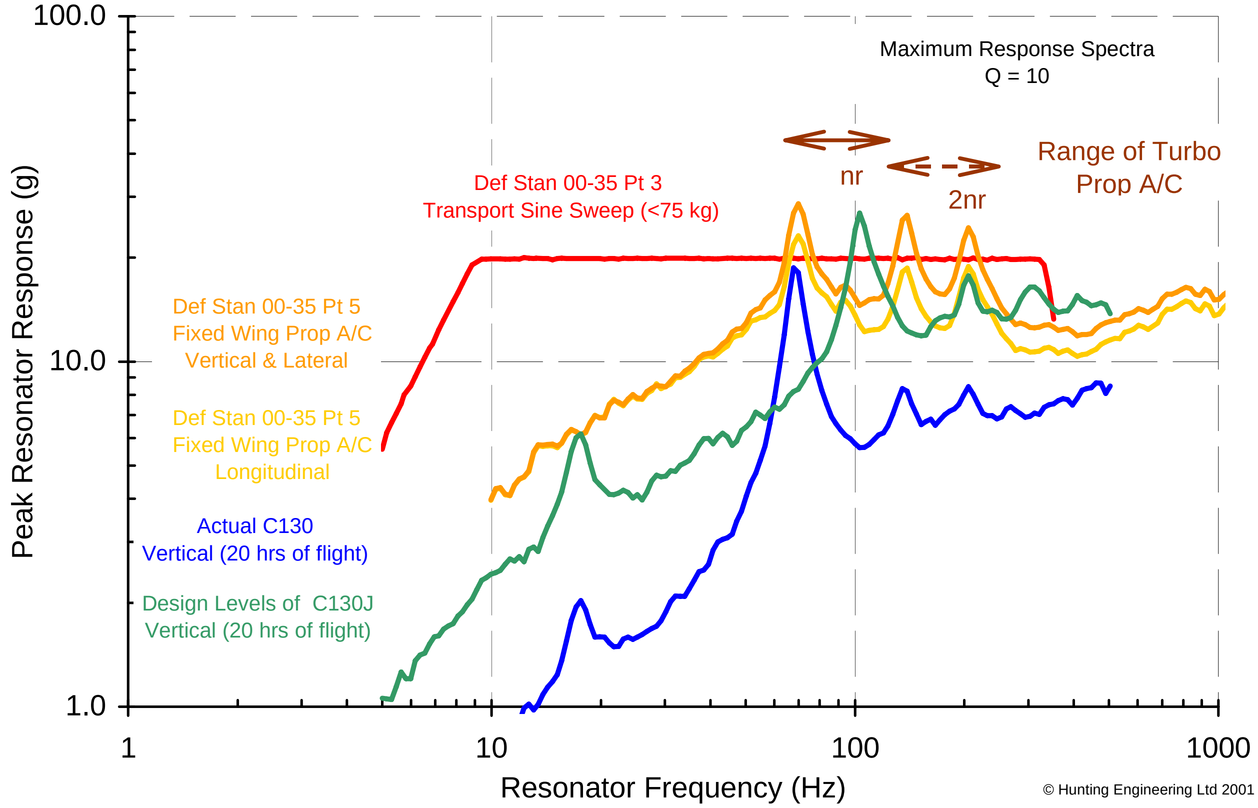

Figure 13 Comparison of Def Stan 00-35 Tests Fixed Wing Propeller Air Transportation - MRS

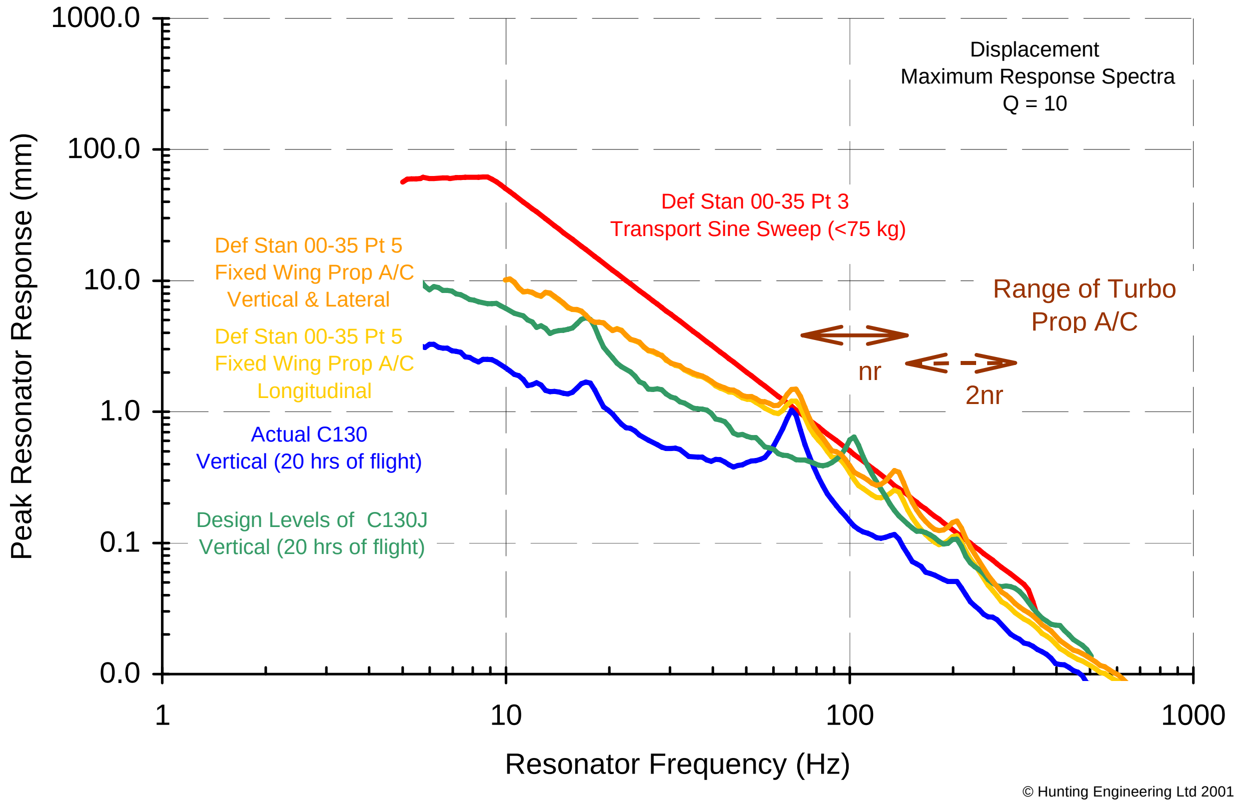

Figure 14 Comparison of Def Stan 00-35 Tests Fixed Wing Propeller Air Transportation - DMRS

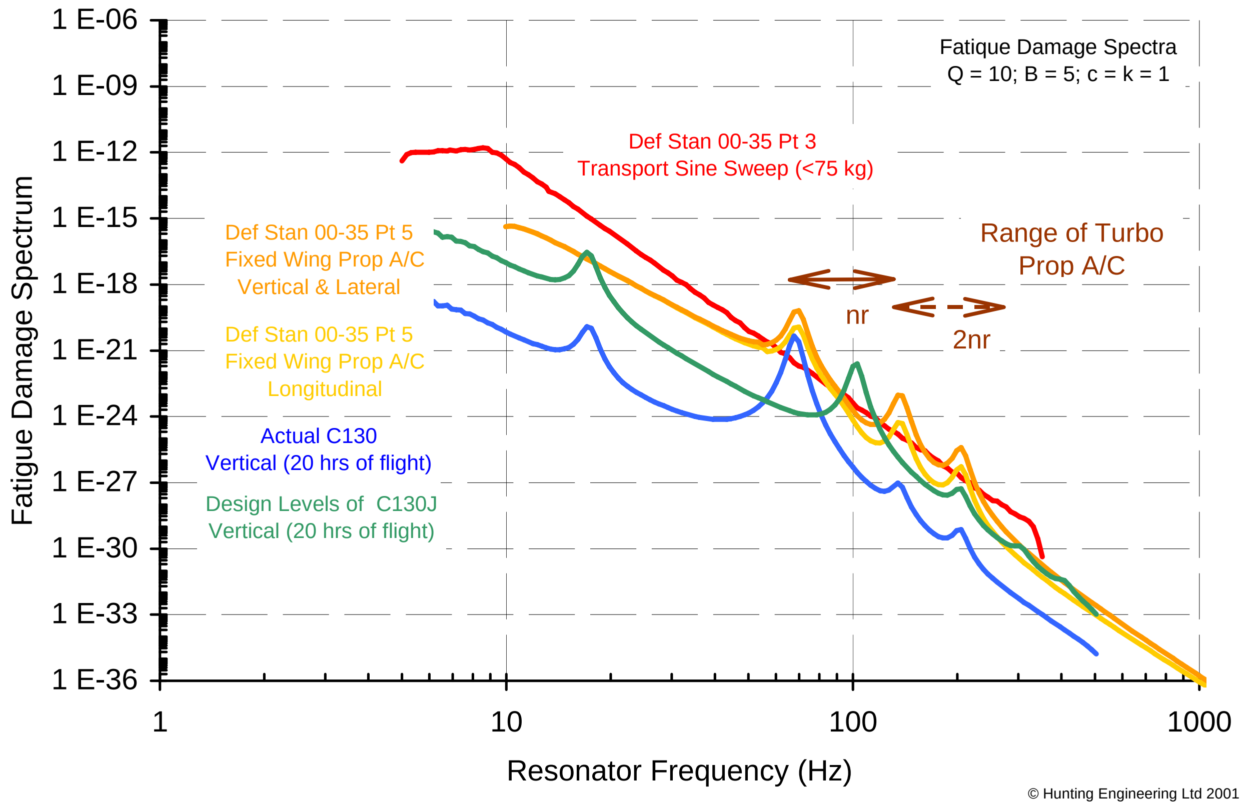

Figure 15 Comparison of Def Stan 00-35 Tests Fixed Wing Propeller Air Transportation - FDS

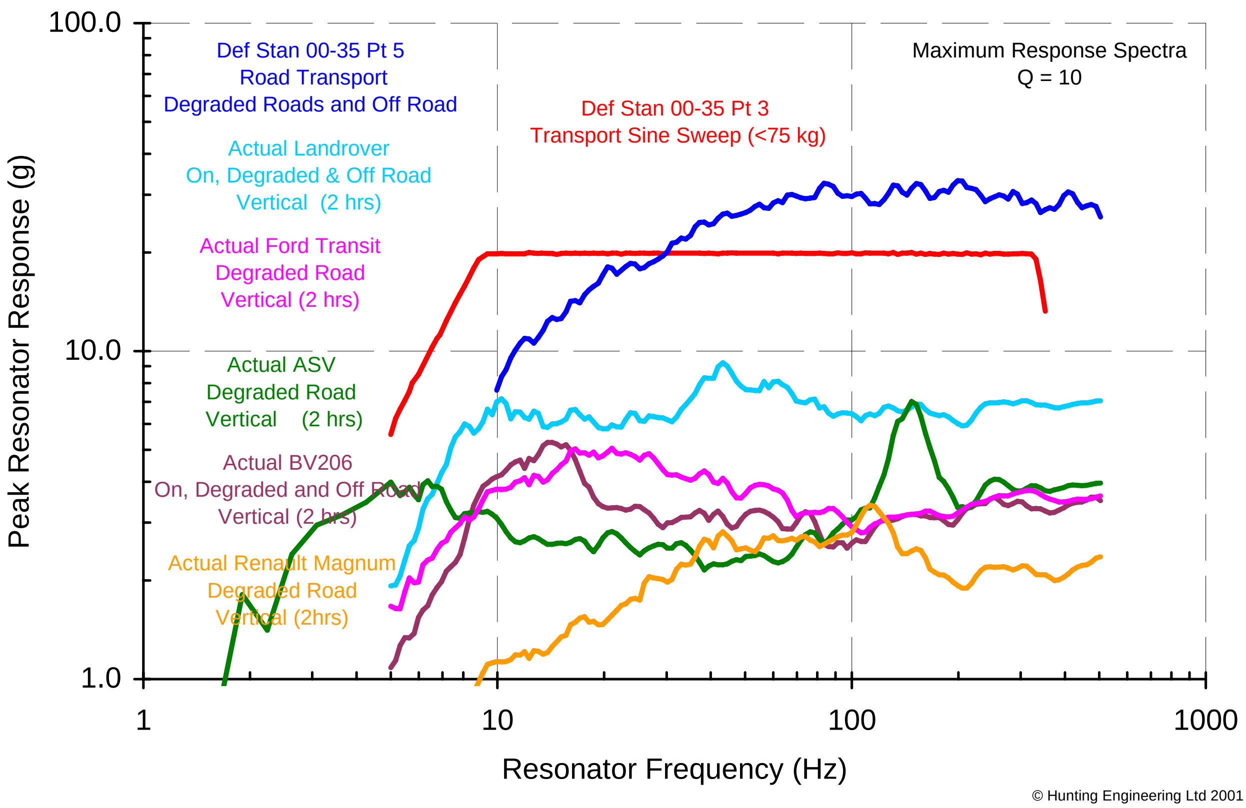

Figure 16 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Wheeled Vehicle Transportation - MRS

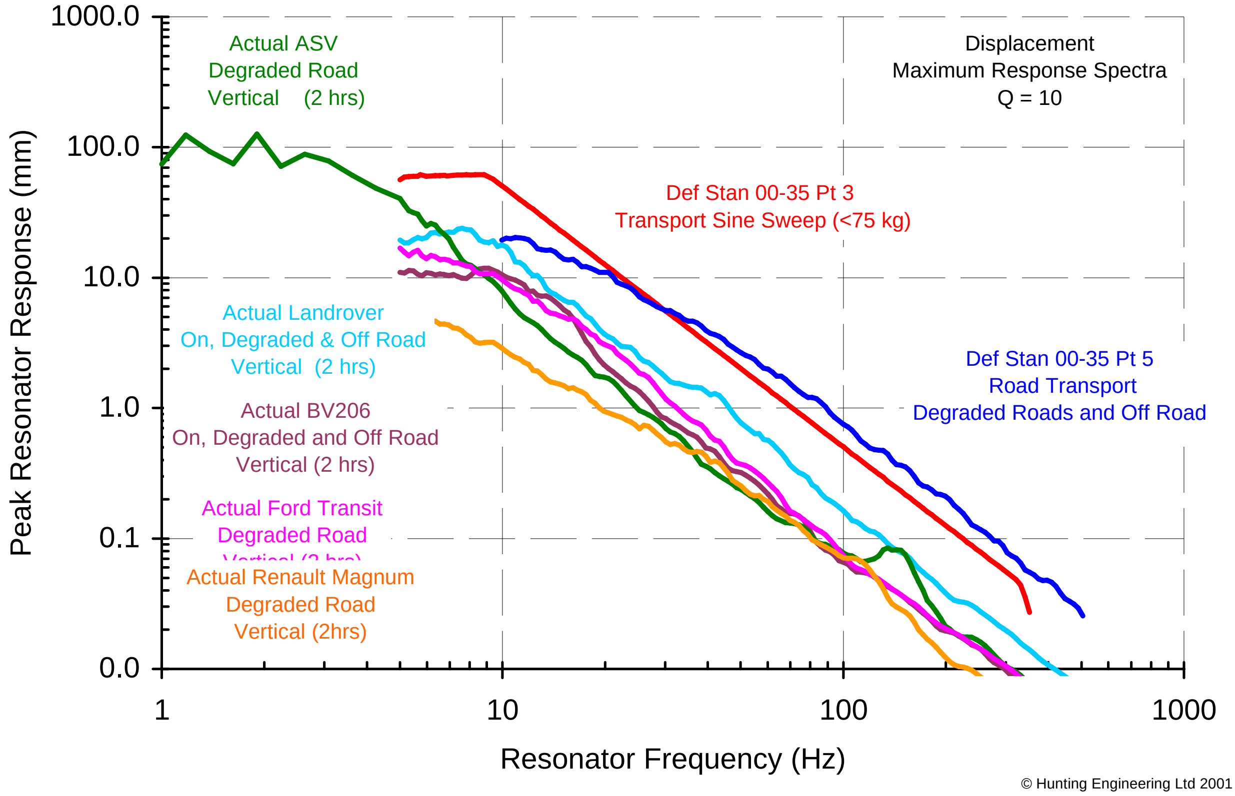

Figure 17 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Wheeled Vehicle Transportation - DMRS

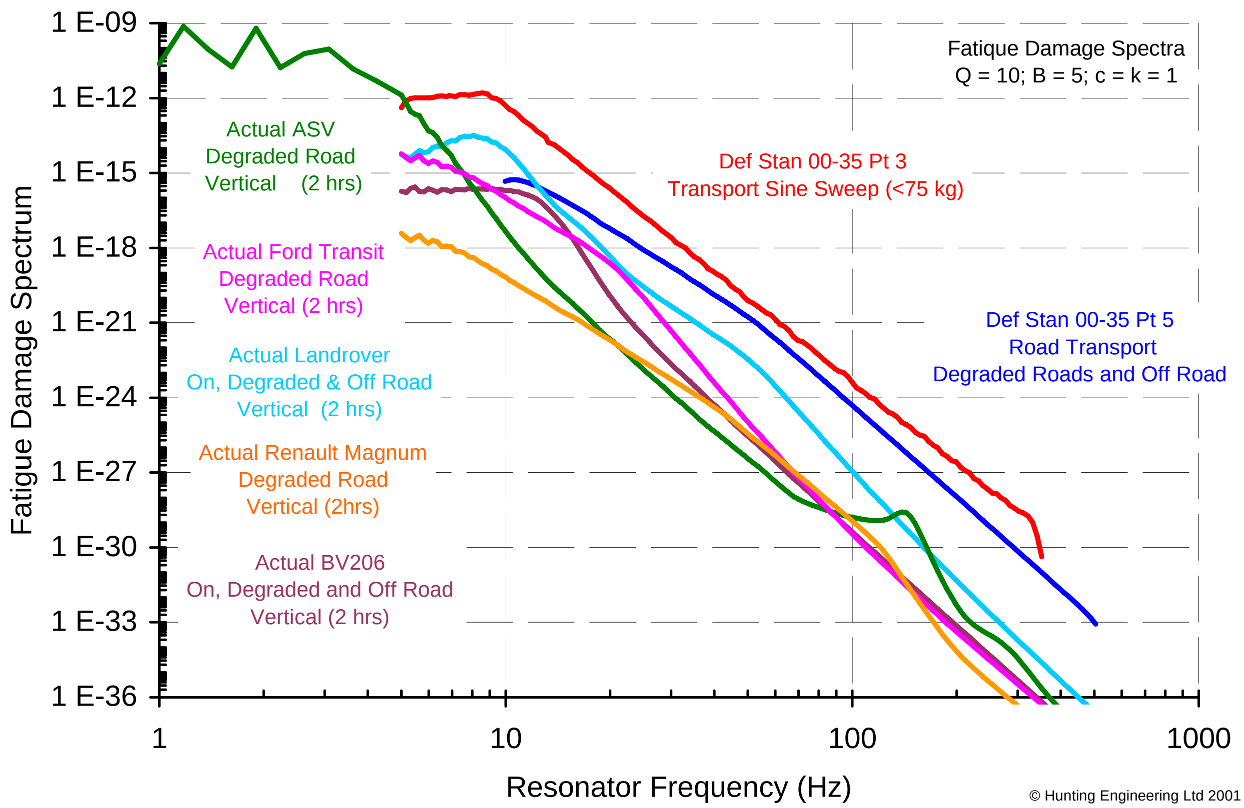

Figure 18 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Wheeled Vehicle Transportation - FDS

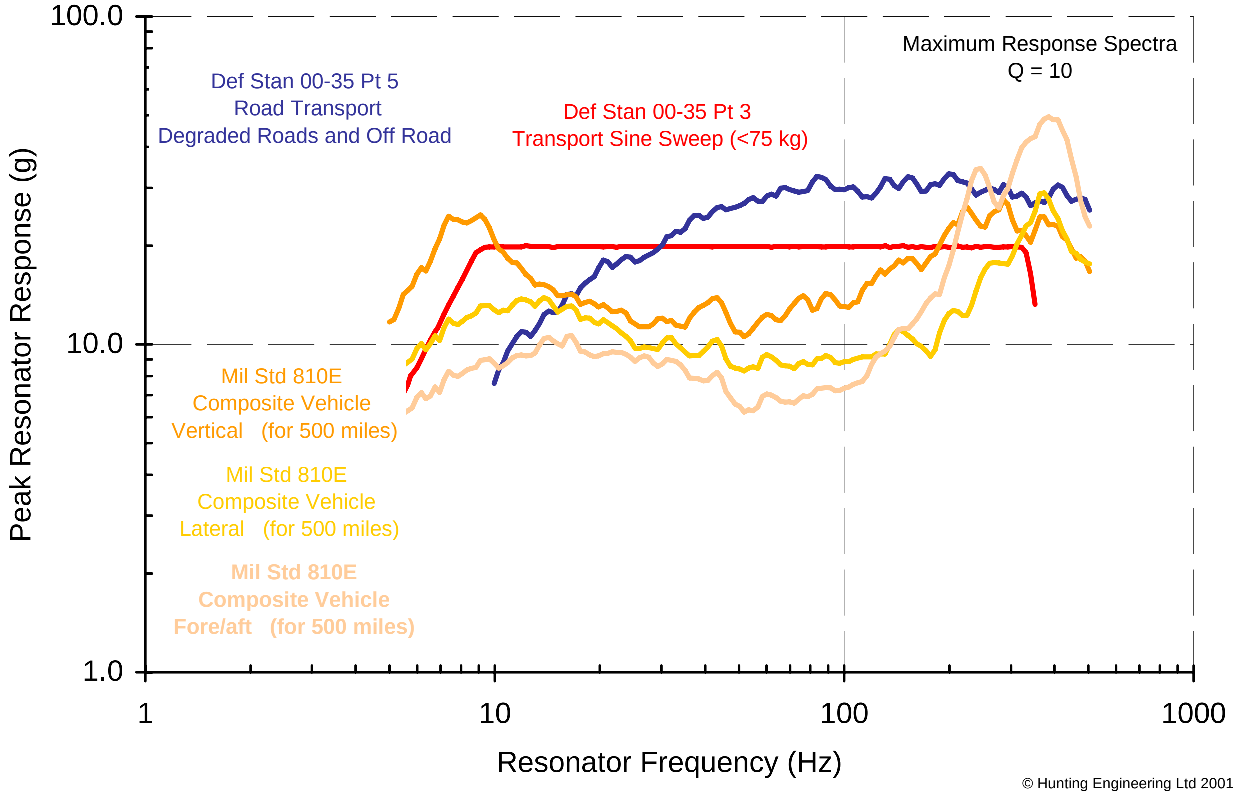

Figure 19 Comparison of Def Stan 00-35 Tests With Mil Std 810F for Wheeled Vehicle Transportation - MRS

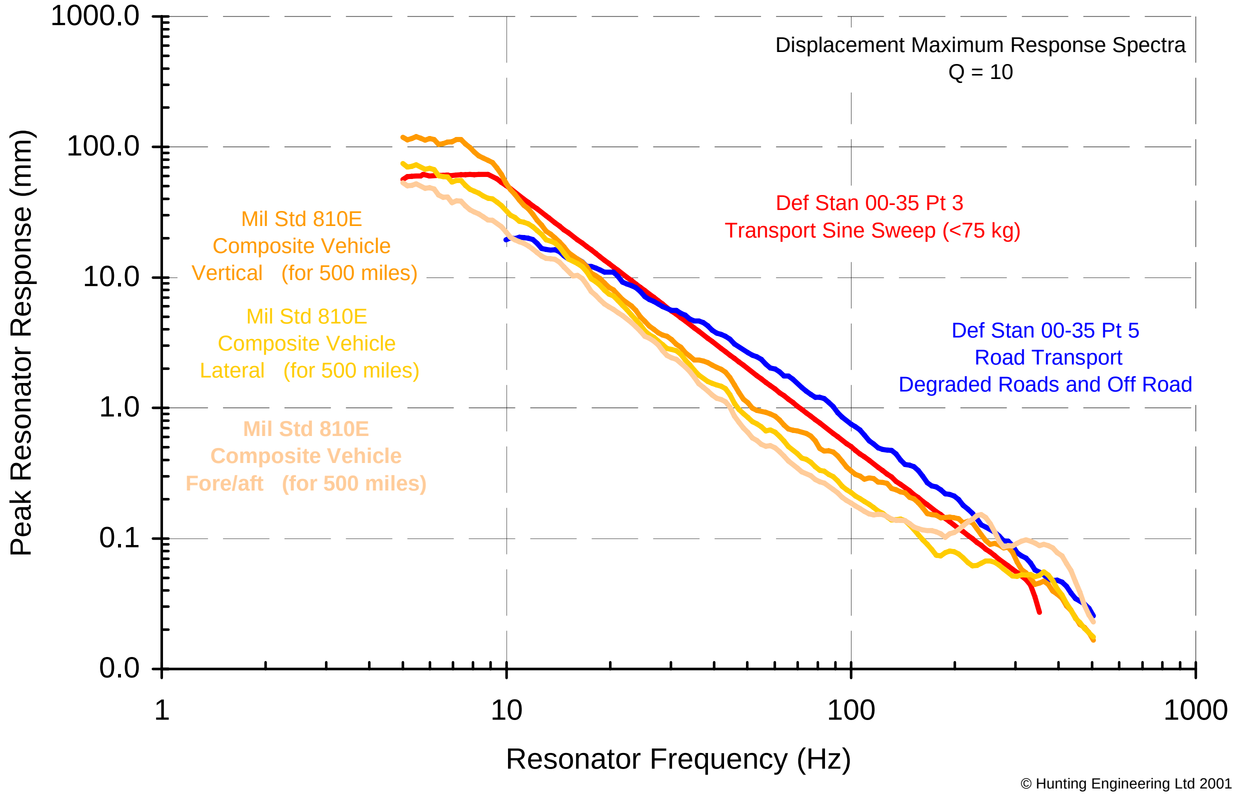

Figure 20 Comparison of Def Stan 00-35 Tests With Mil Std 810F for Wheeled Vehicle Transportation – DMRS

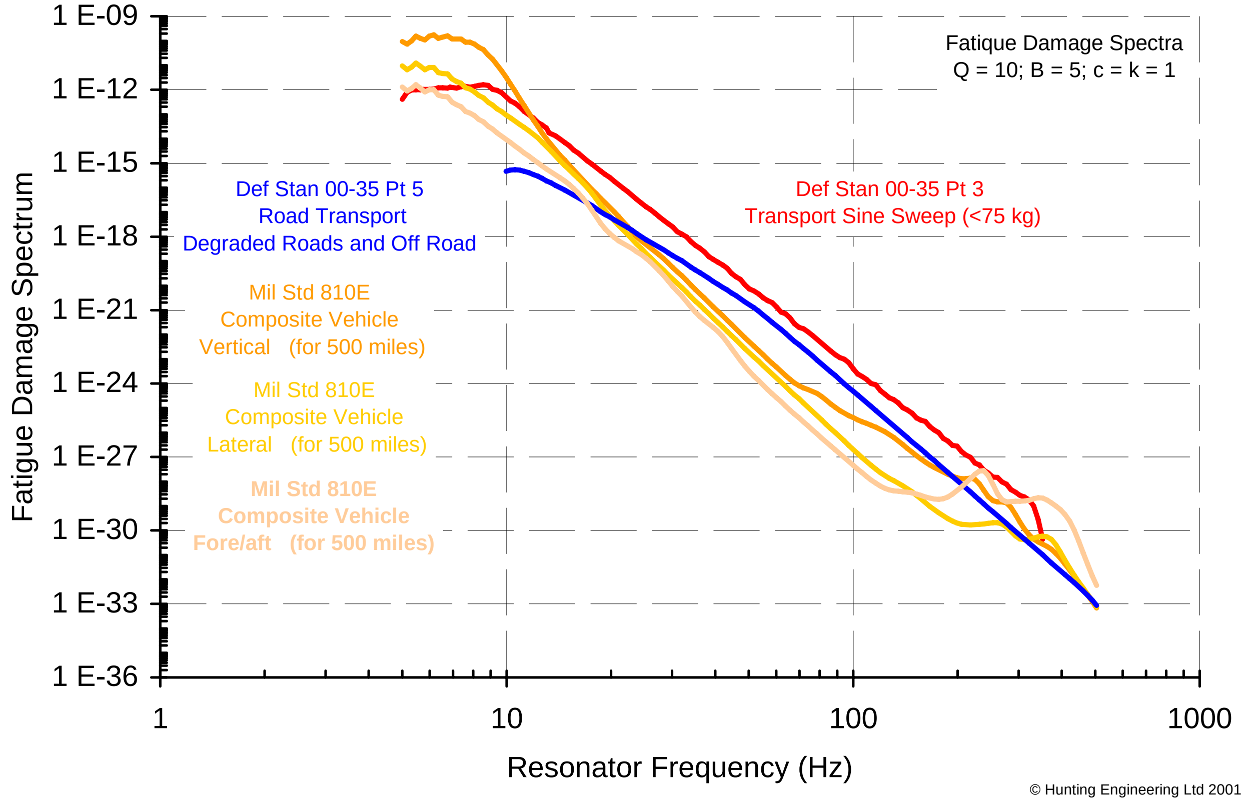

Figure 21 Comparison of Def Stan 00-35 Tests With Mil Std 810F for Wheeled Vehicle Transportation - FDS

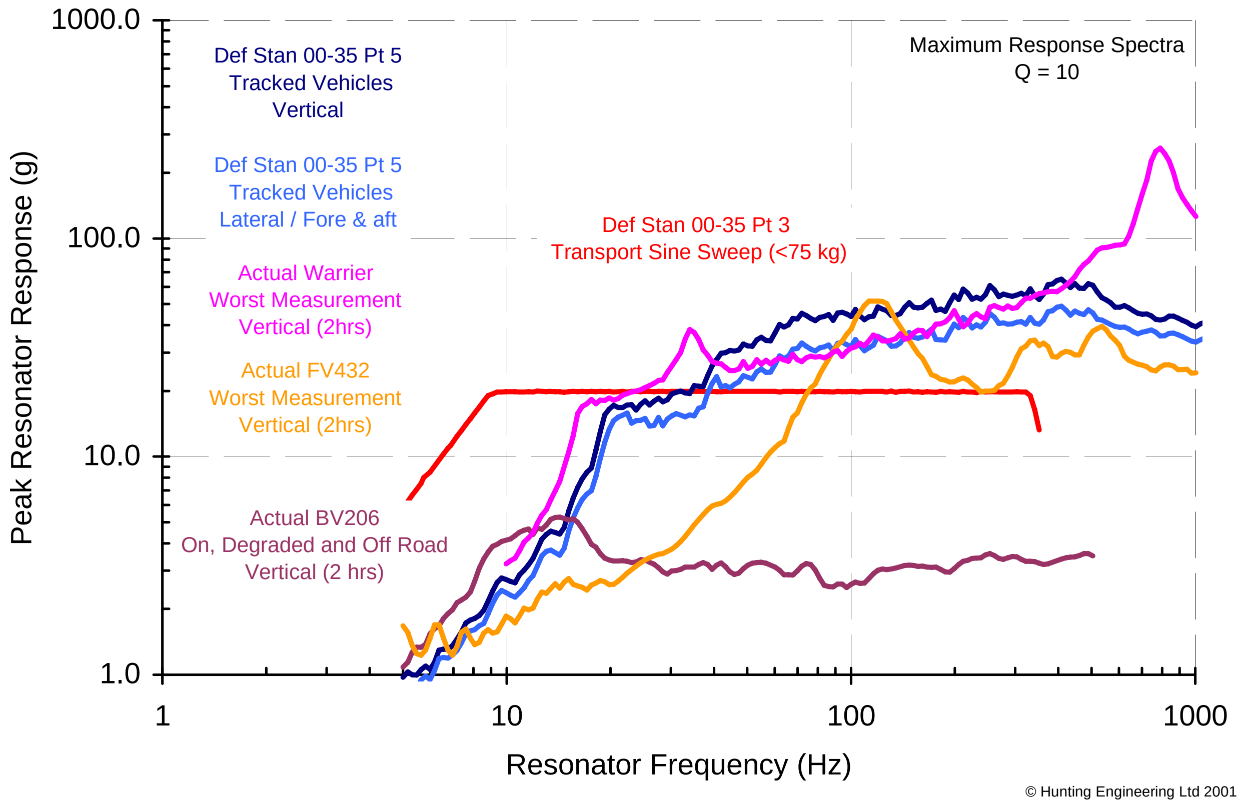

Figure 22 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Tracked Vehicle Transportation - MRS

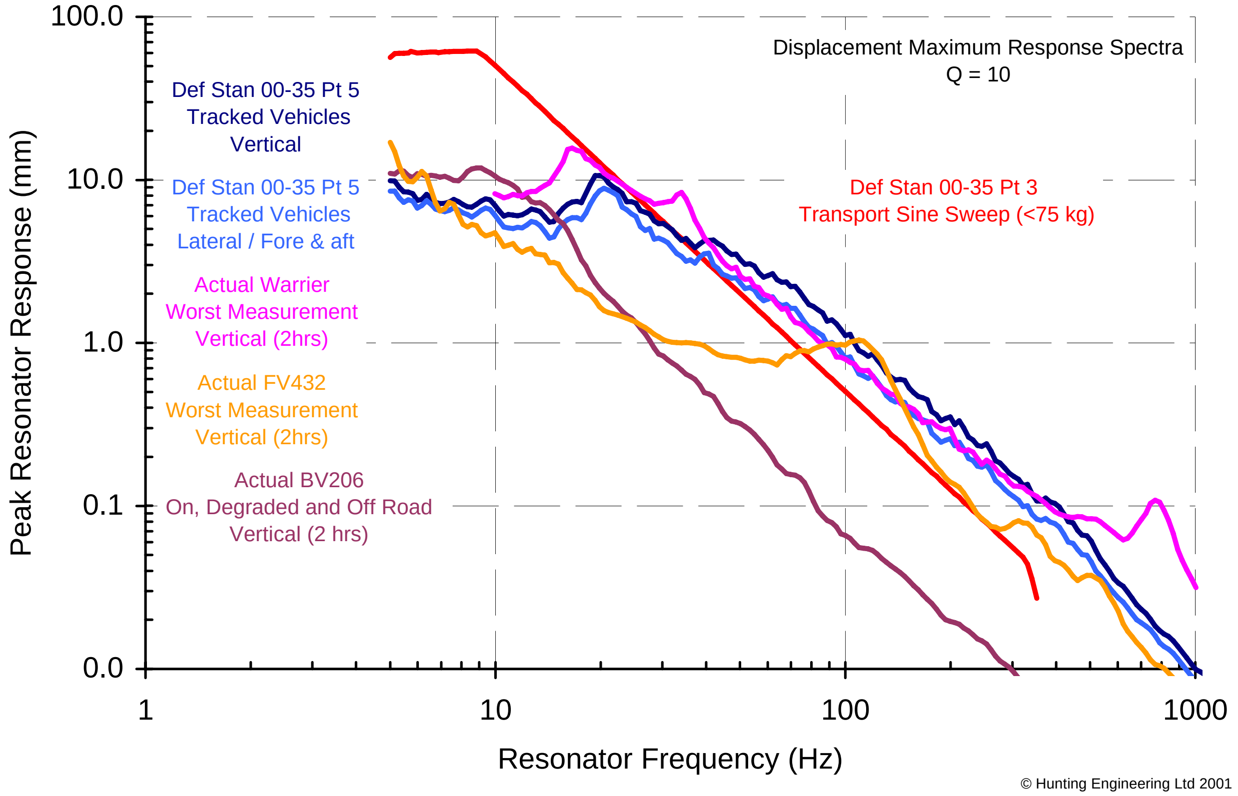

Figure 23 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Tracked Vehicle Transportation - DMRS

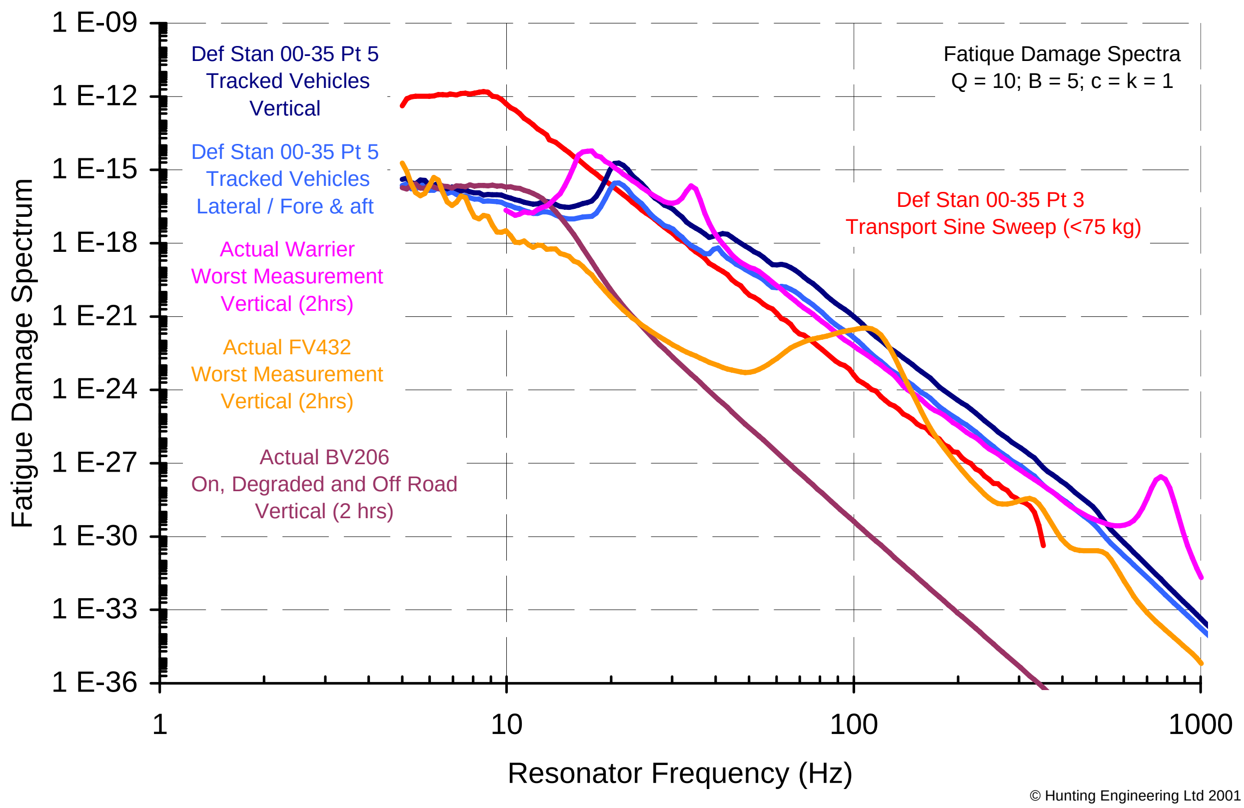

Figure 24 Comparison of Def Stan 00-35 Tests Typical 2nd to 1st Line Tracked Vehicle Transportation - FDS

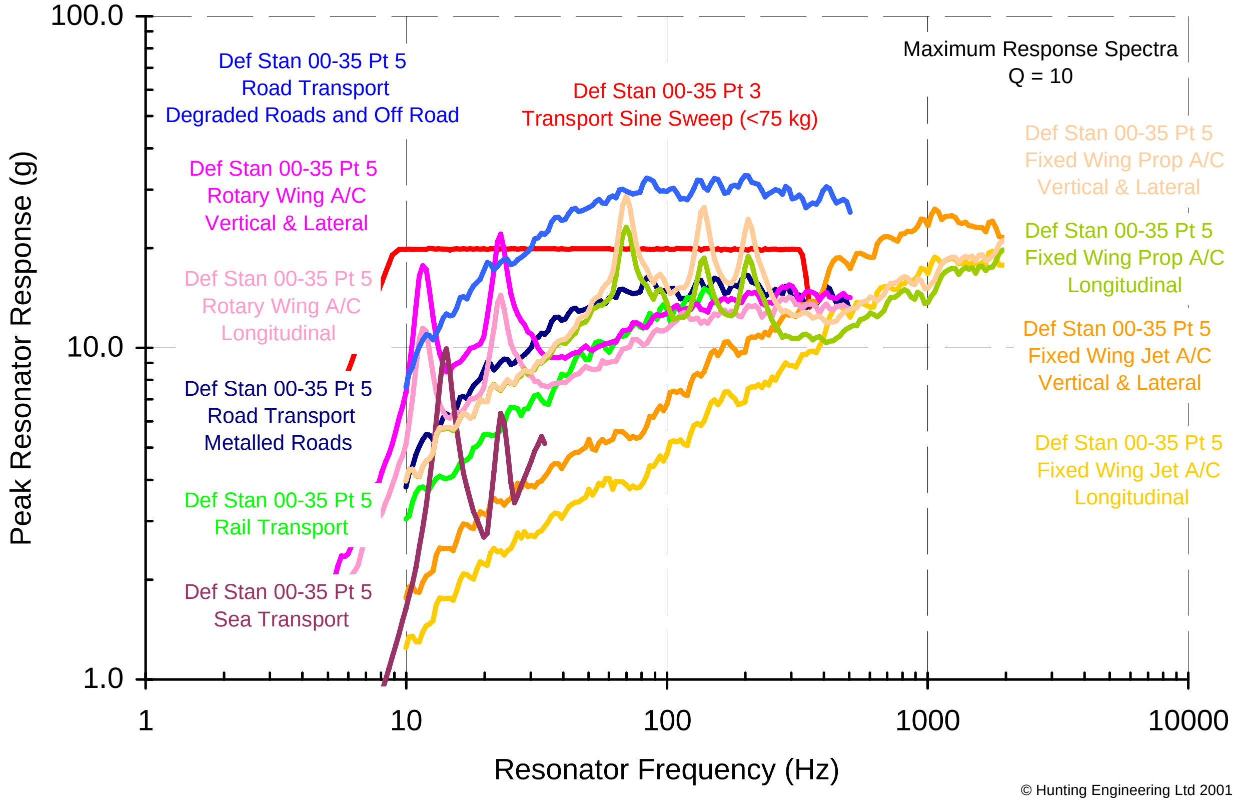

Figure 25 Comparison of Def Stan 00-35 Tests - MRS

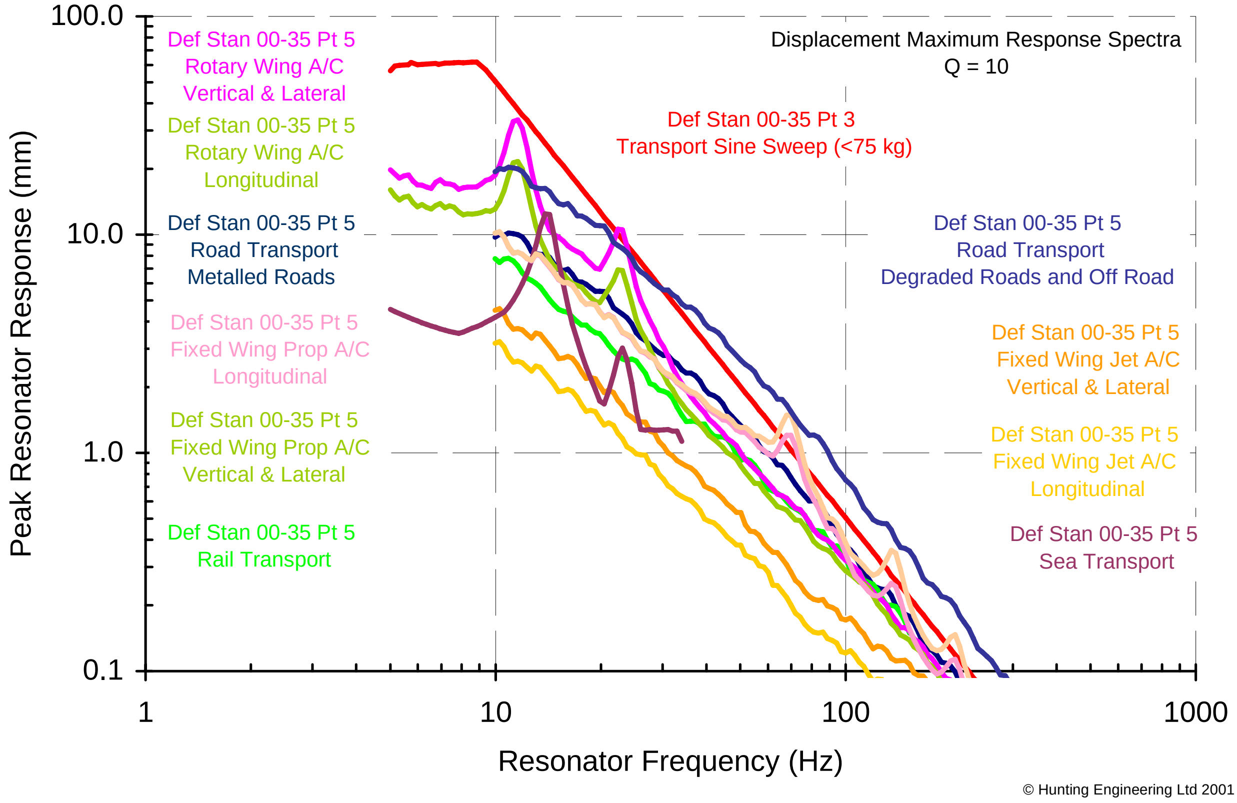

Figure 26 Comparison of Def Stan 00-35 Tests - DMRS

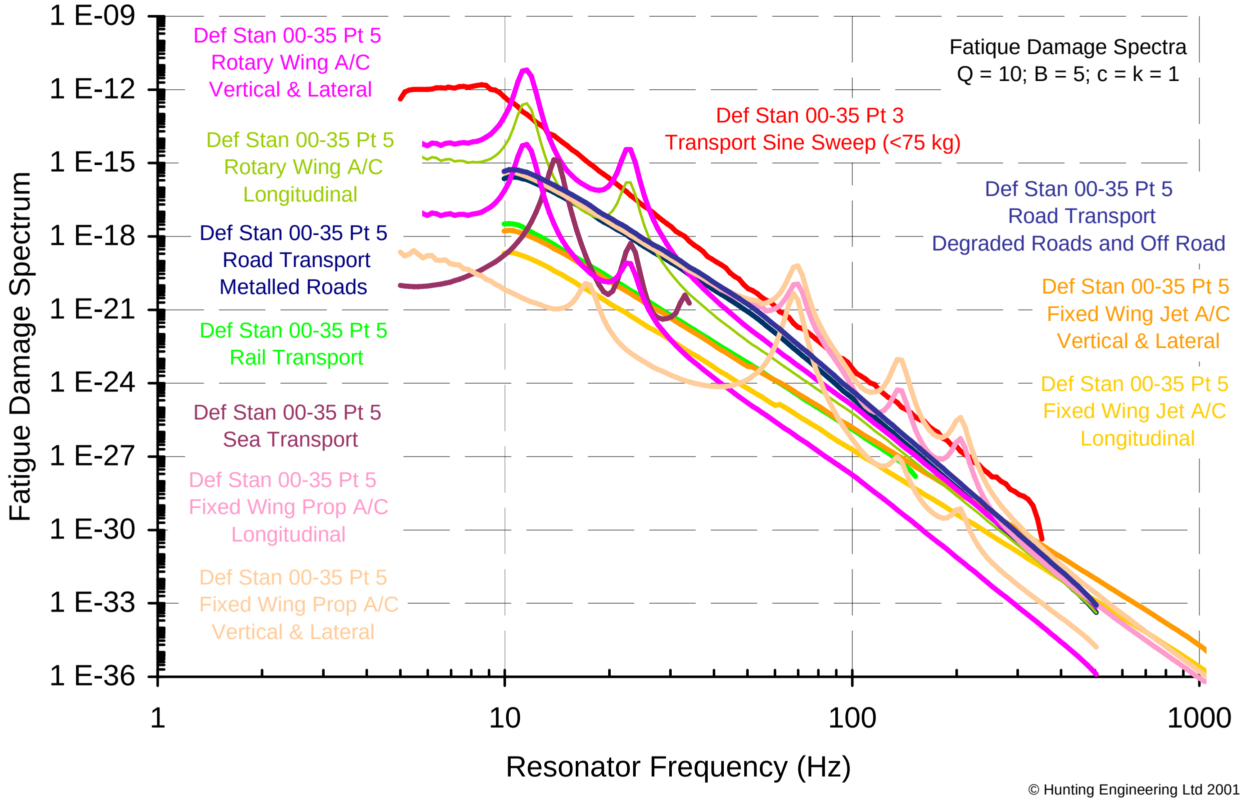

Figure 27 Comparison of Def Stan 00-35 Tests - FDS

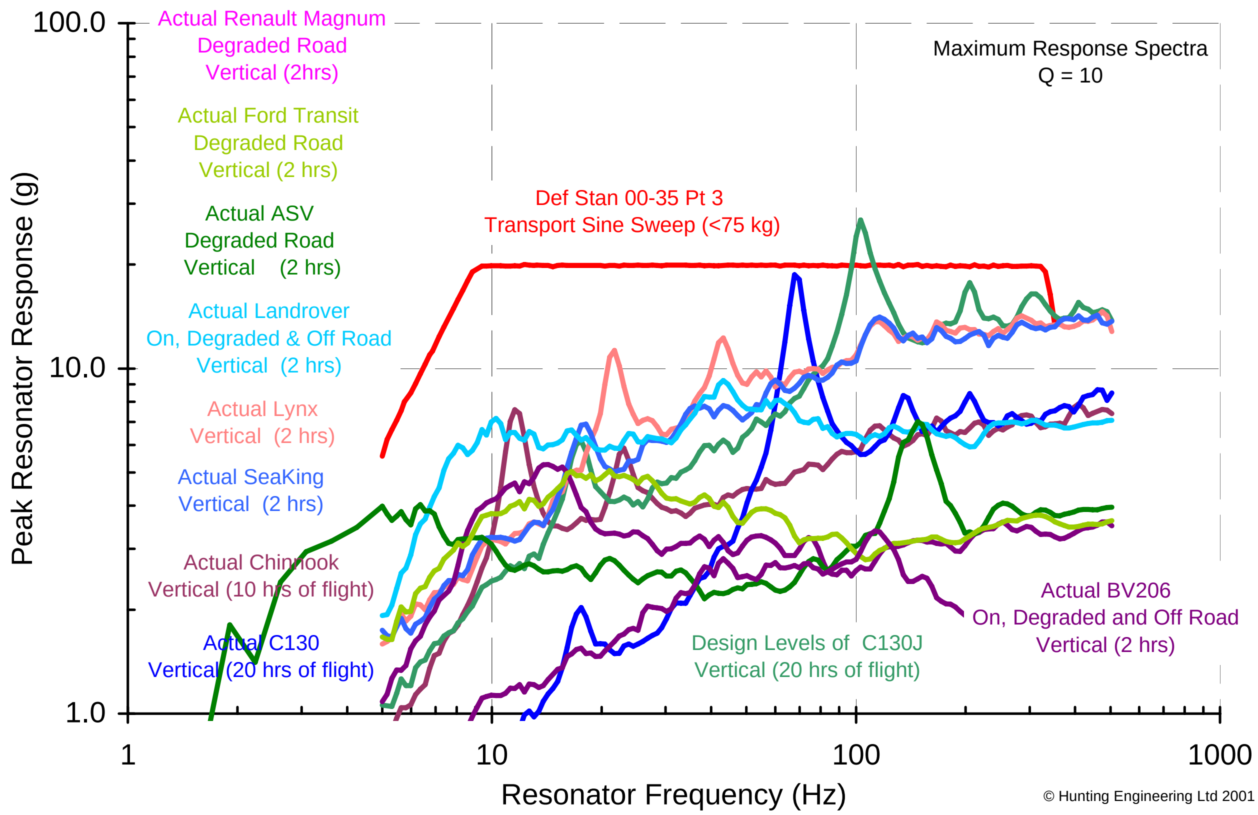

Figure 28 Comparison of Def Stan 00-35 Test With Actual Conditions - MRS

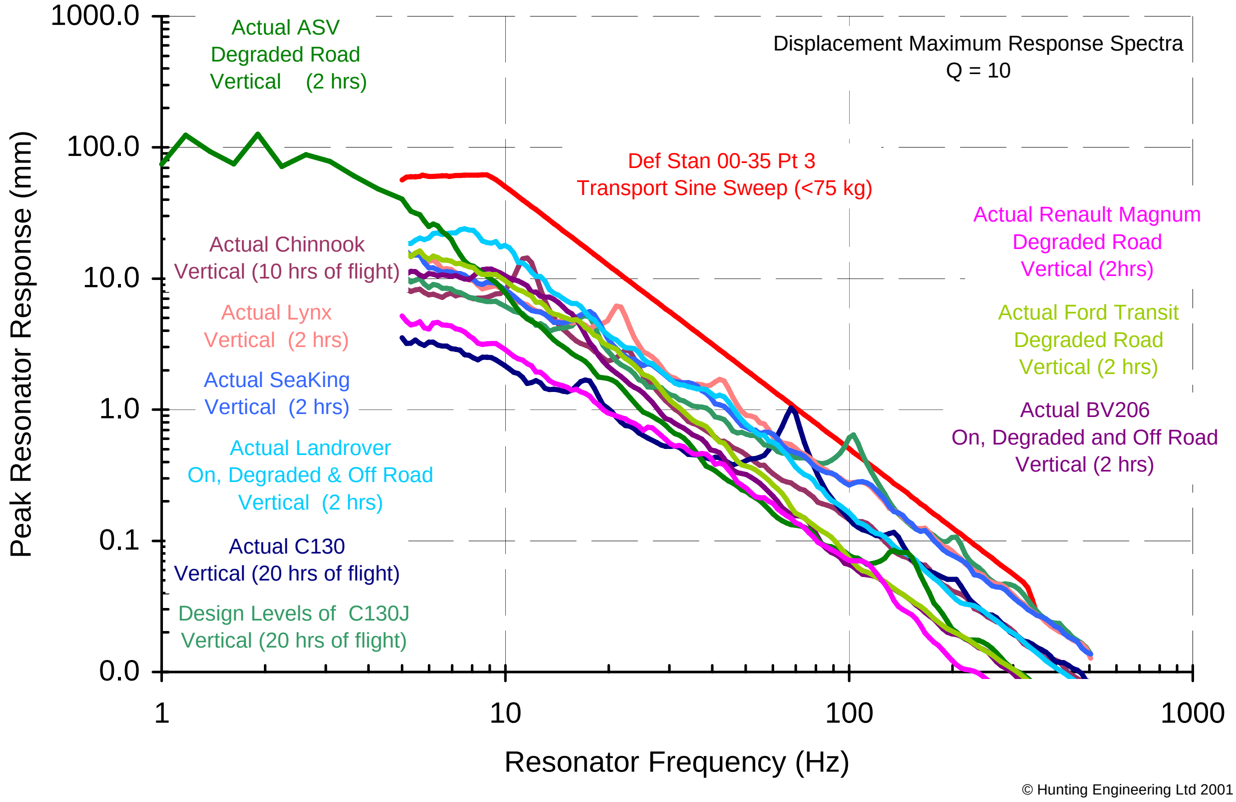

Figure 29 Comparison of Def Stan 00-35 Test With Actual Conditions - DMRS

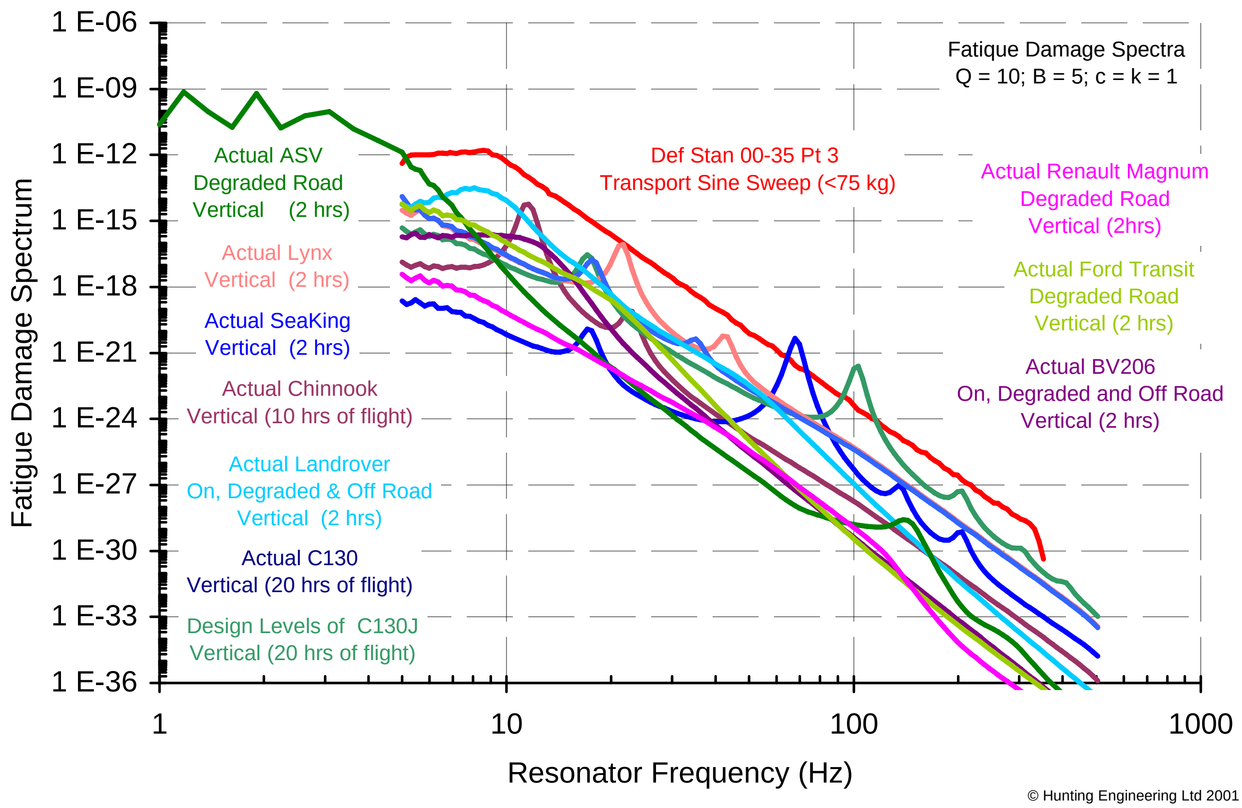

Figure 30 Comparison of Def Stan 00-35 Test With Actual Conditions - FDS

Annex A Maximum Response Spectra and Fatigue Damage Spectra

Background

A - 1. The vibration analysis tools known as Maximum Response Spectra (MRS) and Fatigue Damage Spectra (FDS) were originally developed within the French Atomic Energy Authority. 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 components within the equipment. The normal damage effects addressed were peak acceleration response relating to internal loadings, (by means of Maximum Response Spectra) and fatigue (by means of Fatigue Damage Spectra). However, consideration of absolute and relative displacement is also possible to ensure motions do not exceed the available dynamic spatial envelope.

A - 2. The French Atomic Energy Authority published their work on MRS and FDS in the mid 1970's and papers on the subject were published in France, the UK and the US. Unfortunately, because the method required a lot of computing and specialist computer programming, it was not extensively taken up at that time. To alleviate the computational problems the originator of the method produced solutions specific to random vibration and sine sweeps. By making a number assumptions very significant improvements in computing time could be made. However, the necessary assumptions for random vibration and sine sweeps are different. In consequence, there was always a doubt that any differences may originate from the different assumptions rather than the environment. To encourage wider use of MDS and FDS the originator also produced public domain computer programs, such as DEGAT, able to run on PC's.

A - 3. In recent years the capabilities, have become readily available, to undertake the extensive computing required by MRS and FDS. In addition the use of MRD and FDS as a quantitative basis for setting test severities has been shown to be practicable. The advantage of using MRD and FDS as a quantitative basis for setting vibration test severities is that they can be used to set a traceable severity in terms of both vibration amplitude <u>and test duration</u>. This has been taken up by the French MOD who have embedded the procedure into GAM EG 13. Moreover, the process has received substantial EU research funds and is now a commercially available product (albeit often an expensive one).

A - 4. The advances in computing now allow MDS and FDS to be computed from an arbitrary waveforms. That is it is feasible to compare sine sweeps and random vibrations using the same method and using the same assumptions. Such computations are still quite lengthy but realistic pieces of data can now be processed in an hour or so rather than the several days required previously.

Basic Process

A - 5. The basic process behind MDS and FDS is very similar to that that Shock Response Spectra (SRS). Shock Response Spectra were developed in the US in the 1940's to compare the effects of nuclear tests on structures. These early SRS's were obtained by setting a "comb" made of reeds onto a rigid block. Each of the reeds had a different natural frequency and the tip of each touched a smoked glass plate. The shock from the explosion was transmitted to the reeds via the rigid block. As a result of the shock each reed vibrated and its maximum displacement was witnessed by the smoked glass plate. The reeds vibrated differently, depending upon the characteristic of the shock and gave a "response spectra" which could be used to characterise the shock. The main technical differences between these early SRS measurements and todays MRS/FDS is that the latter address the peak acceleration response of the "reeds" vibrations (rather than shock) and establish the fatigue damage that would have accrued on the "reed" during its vibration response motions.

A - 6. Today, those early measurements, are all now done on the computer. Unfortunately, as often can be the case, simulating these early "simple" measurement arrangements on a computer is actually fairly complicated. Each "reed" in those early experiments is now a base excited single degree of freedom (SDOF) system comprising a mass, spring and damper. The mass and stiffness are set to give a particular resonator frequency, the value of damping is set by the analyst. The SDOF is excited by the shock/vibration under consideration and its response established. This response can be interrogated to give peak acceleration response, peak displacement response or accrued fatigue damage. For a full SRS/MDS/FDS spectra the process is repeated for a range of SDOF resonator frequencies (typically several hundred).

A - 7. Hunting Engineering have become involved in the use of MDS/FDS as a consequence of co-ordinating a pan-European exercise to compare different methods of setting vibration test levels from real world measurements. Of the various methods used for that work only two addressed the different effects that the measurements would have on real products. Those methods were MDS/FDS as well as the Amplitude Probability Density approach. As it transpired the two approaches were complimentary.

A - 8. The process used by Hunting Engineering for MDS/FDS allows an arbitrary waveform to be used. By using the same process, regardless of the type of vibration, doubts concerning different inherent assumptions of different methods can be avoided. Also when used as a comparison tool, the value of SDOF damping selected by the analysts is not important. The same is true of the values assumed for material damping (although these would matter if FDS were used to give specific life estimates). This has been well illustrated by Lalanne in Reference A-1.

A - 9. The actual method used here for computing MDS and FDS from an arbitrary waveform is based upon a method developed by Thomas Svensson of the Swedish Testing and Research Institute (Ref. A-2). In reality Svensson adopted the Holm and de Mare (Ref. A-3) model for fatigue life predictions to the FDS problem. The main reason for this approach, as opposed to say rainflow counting methods, is that it had been shown to be more reliable with low irregularity factor data. Svensson made no recommendation as to the method to be used to establish the response time history from which the fatigue life estimates could be made. Unfortunately, the requirements for FDS do not permit use of most of the recent classic Shock Response Spectra methods for this purpose as a full time response is required. However, some of the older Shock Response Spectra methods are suitable for this purpose. The actual method used to break the arbitrary waveform into a number of small blocks. For each block the Fast Fourier Transform (FFT) is computed, multiplied by the complex response characteristics of the SDOF. From this product the resultant time history is obtained by computing the inverse FFT. Although this method does have limitations, these are very well documented and, in most cases, solutions available.

Interpretation of Results

A - 10. The main value of SRS, MDS and FDS is that they are all a measure of how a notional component will reacts to the applied vibration, be it sine or random. That they are a tool to compare potential damage mechanisms on the internal components of an equipment.

A - 11. A Maximum Response Spectra indicates the peak acceleration response the various resonators would experience. Maximum Response Spectra are usually used to compare vibration amplitudes. They tend to have gradually increasing amplitude with frequency. This is because a single degree of freedom resonator is akin to a simple filter responding to the lower frequency excitations but not the higher frequencies. That is the greater the resonator frequency the more lower frequency vibrations are able to excite the resonator. When broad band random vibrations are used the consequence of this is that the peak acceleration response shows a gradually increasing amplitude with frequency. However, this is not so pronounced for a sine sweep which shows a much “flatter” MDS characteristic.

A - 12. The acceleration amplitude of a Maximum Response Spectra is directly related to acceleration loads experienced by potential components. As an example if the MRS of a test shows a damage value twice as great as that from the vibrations from a single flight; then the test would be indicate a margin of 2 on internal equipment loads.

A - 13. Fatigue Damage Spectra are the main reason for doing MDS / FDS computations. FDS extends the comparison of vibration amplitudes, undertaken using MDS, to allow a comparison of test durations. FDS is one of the few techniques available for doing this. The most noticeable characteristic of an FDS is the rapidly falling damage amplitude. Typically the damage axis may encompass 20 or more decades of amplitude. This is because, in absolute terms, fatigue damage is strongly related displacement amplitude and displacement responses are dominantly generated by the lower resonators. However, this does not necessarily mean only the low frequency FDS values are of concern. The resonators are been used to represent the dynamic characteristics of internal equipment and internal equipment usually has a high natural frequency.

A - 14. The damage amplitude of a Fatigue Damage Spectra is directly related to fatigue life. As an example if the FDS of a test shows a damage value 10 times greater than that from the vibrations from a single flight; then the test would be indicates as been equivalent to 10 such flights.

A - 15. Four assumed parameters are normally quoted on a FDS curve these are Q, b, k and c. In practical terms none of these has any significant influence when FDS is used as a comparison tool (as they are here). However, they would have an effect if the FDS were to be used to compute absolute fatigue life. The meaning of the four parameters are;

i. The parameter Q is a measure of the SDOF damping. In this case a value of 10 corresponds to a damping level of 5% critical. This is reasonably representative of equipment and is commonly adopted for both SRS and FDS work.

ii. The parameter b is the assumed slope of the material fatigue or Wohler curve. It is defined by the relationship $Ns^b=c$, were N is the number of fatigue cycles associated with a stress loading s. For defence work within the UK the value b is usually assumed as 5 for vibration life assessment purposes (and was originally derived by RAE Farnborough). However, when comparing two sets of FDS values the difference is for all practical purposes independent of the value of b.

iii. The parameter k is the constant in the linear equation relating acceleration to stress. For FDS comparison purposes it is usually taken as unity.

iv. The parameter c is defined by the relationship $Ns^b=c$. For FDS comparison purposes it is usually taken as unity.

v. The parameters k and c are taken as unity because they are constants in the FDS computations. That is they constitute a common multiplier equally applicable to the damage estimate for all resonators. The applicable multiplier is k^b/c.

References

A-1. The Mechanical Environment Test Specification Development Method, Christian Lalanne, 3rd edition, October 1997, Centre d'etudes Scientifues et Techniques d'Aquitaine.

A-2. Utilization of Fatigue Damage Response Spectrum in the Evaluation of Transport Stresses, Thomas Svensson, Swedish Testing and Research Institute, SP Report 1993:13.

A-3 A Simple Model for Fatigue Life, S. Holm & J. de Mare, IEEE Transactions on Reliability, Vol 37 No 3, 1988

INTENTIONALLY BLANK