An On-Road Shock & Vibration Response Test Series Utilizing Worst Case and Statistical Analysis Techniques*

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Defining the maximum expected shock and vibration responses for an on-road truck transportation environment is strongly dependent on the amount of response data that can be obtained. One common test scheme consists of measuring response data over a relatively short prescribed road course and then reviewing that data to obtain the maximum response levels. The more mathematically rigorous alternative is to collect an unbiased ensemble of response data during a "long" road trip. This paper compares data gathered both ways during a recent on-road certification test for a tractor trailer van being designed by Sandia.

INTRODUCTION

On-road shock and vibration tests are often conducted to gather response data for use in certifying components and cargo that must ride on a truck. Just such a test series was conducted for the prototype unit of a new tractor trailer van being designed by Sandia. The test series was broken into two parts: 1) a relatively short distance (≈160 mile) test utilizing a thirty one (31) channel Data Acquisition System (DAS), and 2) a cross country road test utilizing a single tri-axial accelerometer.

The goal of the short road trip (designated as the Moriarty trip) was to obtain the "worst case" response for all of the critical locations in the trailer. The length of this road test was constrained by two things: 1) the limited availability of the prototype trailer due to an aggressive development program, and 2) the fact that test personnel were required to operate the DAS. The shortness of the test route placed a constraint on our confidence that we had indeed measured the "worst case" environment.

Fortunately, the opportunity arose to gather shock and vibration data on a cross-country road trip (designated as the DC trip). The one restriction placed on this test was that it could not interfere with the primary objective of the road trip so it was not possible to fully instrument the trailer as had been done for the Moriarty trip. Therefore, it was decided to gather statistical data on a single, representative response location. The "worst case" Moriarty response data would then be compared against the statistically significant DC response data at the same location in order to establish the probability of occurrence of the Moriarty data. The results obtained for that location would then be applied to the entire trailer.

WORST CASE VIBRATION MEASUREMENTS (MORIARTY TRIP)

The Moriarty road course consisted of approximately 160 miles of Interstate highway, rural highway, city streets, and unpaved roads. Rough sections of road (uneven pavement, potholes, bridge joints, etc.) were identified during a pre-test drive. Several smooth sections of roadway were also identified for reference purposes.

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DISCLAIMER

Thirty-one (31) accelerometer channels were recorded during the test. The DAS was turned on during the pre-selected sections of road. Twenty seven (27) vibration events (including a measurement of the noise floor) were analyzed from the entire record and grouped by road type for the purpose of establishing the maximum vibration environment for the Moriarty road course.

The solid curve in Figure 1 (designated mor env...) is the envelope of the 1/6th octave bandwidth Power Spectral Densities (PSDs) for all of the vibration events analyzed from the Moriarty trip for the fwbz accelerometer. Straight line versions of this envelope and others just like it for other locations within the trailer will form the basis for the laboratory test specifications for the trailer's components and cargo. The other two PSDs in this plot will be described below.

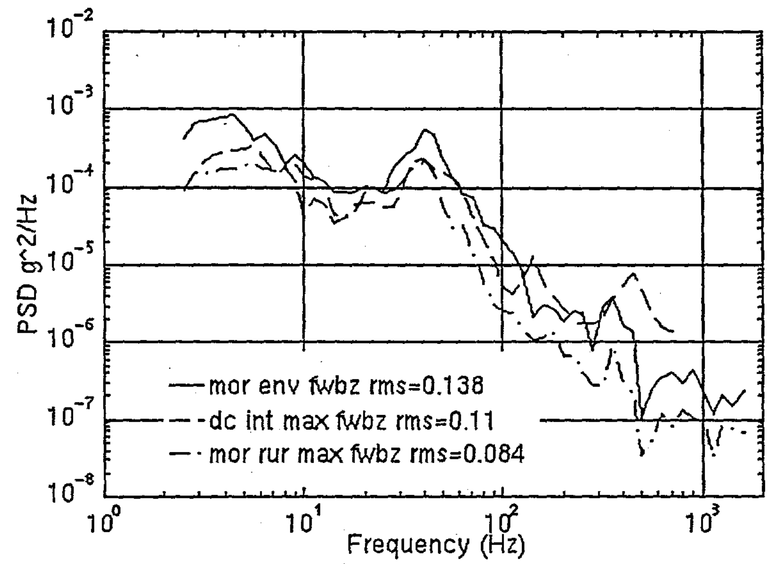

Figure 1: Maximum Vibration Responses for Moriarty and DC Road Trips

STATISTICAL VIBRATION MEASUREMENTS (DC & MORIARTY TRIPS)

The DC road course consisted of a round trip from Albuquerque, New Mexico to Oak Ridge, Tennessee. The DAS used for this portion of the test was a self-contained tri-axial accelerometer and data recorder package supplied by Instrumented Sensors Technologies (the model EDR-3™). This recorder can be programmed in one of two modes: 1) record data once every N minutes, or 2) record the M highest events (based on peak acceleration g's).

For the outbound trip the EDR-3 was programmed to record once every 20 minutes (a total of 107 events were recorded). Events recorded when the trailer was sitting still were deleted from the database (74 "active" events remained).

The EDR-3 was placed on the forward section of the trailer bed near the fifth wheel. Due to the relatively low response levels recorded during the trip, only the vertical channel (designated fwbz) recorded any response above the noise floor.

Prior to the Moriarty test series it was assumed that the response levels for rural highways would be significantly higher than those for the DC trip since the DC road course consisted primarily of Interstate highways. Once it became apparent that the response levels for the Moriarty trip were not significantly higher than those for the DC trip, it was deemed beneficial to have statistical information on the other road types as well. Fortunately, the DAS had been left on continuously for almost 1 hour while the trailer was traveling on rural highways (which is the second most common road type after Interstate highways). Thirty-four (34) segments of data equally spaced in time were evaluated in the same manner as the DC Interstate trip to obtain statistical data for rural highways.

The dashed curve in Figure 1 (designated dc int...) is the PSD for the highest g_{rms} event measured during the DC trip. The dash-dot curve in Figure 1 (designated mor rur...) is the PSD for the highest g_{rms} event in the rural highway statistical database.

In order to determine the statistical significance of the Moriarty envelope PSD in Figure 1, it was necessary to derive an estimate of the Probability Density Function (PDF) for the DC Interstate and Moriarty rural highway databases. The PDFs presented in this paper were generated using an algorithm discussed by [Silverman, 1986] and implemented in a routine supplied by Norm Hunter of Los Alamos National Laboratories.

Given the relatively consistent shapes of the PSDs in the database, it was decided to compute the PDFs using only the g_{rms} values in order to reduce the computational effort (the more rigorous line by line analysis was not considered necessary for the purpose of this exercise). Figure 2 presents the resulting PDFs for the DC Interstate and Moriarty rural highway databases (designated dc int... and mor rur... respectively). The dash-dot line in Figure 2 (designated mor env...) denotes the g_{rms} level for the worst case Moriarty trip PSD envelope shown in Figure 1.

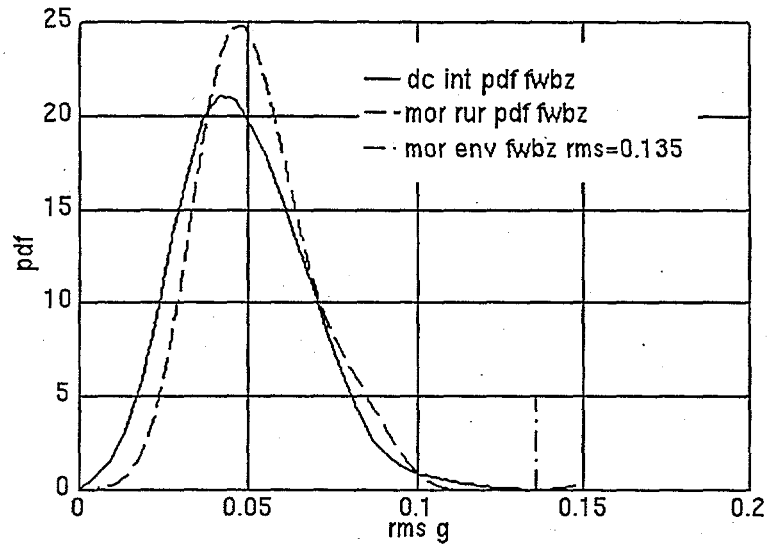

Figure 2: Probability Density Functions for DC and Moriarty Vibration Databases

SUMMARY OF VIBRATION RESULTS

Using the Cumulative Density Functions (CDFs) for the DC and Moriarty databases, which are simply the integrals of the corresponding PDFs, it can be shown that the worst case Moriarty envelope exceeds the expected random vibration response level 99% of the time for Interstate and rural highways.

However, due to the relatively small size of the DC and Moriarty databases (74 and 34 segments respectively), it was decided to make an estimate of the confidence interval associated with these probabilities. The estimation of the confidence interval was made somewhat more difficult by the fact that the profile of interest (the Moriarty envelope) did not come from the same database as the PDF. Given this constraint, it was decided that a simple, yet conservative approach would be to use the Distribution-Free Tolerance Limit (DFL) [Piersol, 1994] to compute the confidence interval for the maximum g_{rms} events recorded for the DC and Moriarty rural highway databases and then to infer that the Moriarty envelope would have at least as high of a confidence interval since its g_{rms} level is higher than that of the maximum single event recorded in each of those databases. The formula for computing the confidence interval, γ, using the DFL is presented in Eq. (1).

$$\gamma = 1 - \beta^{n} \tag{1}$$

Where β is the probability and n is the number of data points in the ensemble. Based on the DC database (74 events), the DFL predicts that the Moriarty envelope PSD exceeds the expected random vibration response level 99%

of the time for Interstate highways with at least a 52% confidence interval (P99/52). However, based on the Moriarty rural highway database (34 events), it was necessary to reduce the probability claims for the Moriarty rural highway envelope PSD to 98% probability of occurrence in order to obtain a minimum confidence interval of 50% (P98/50).

ACCELERATED VIBRATION TESTING

An important side benefit of the statistical data comes into play when determining how long a laboratory test must be conducted in order to approximate the fatigue damage associated with the field environment. The total estimated service life for the trailer components is several thousands hours, while cargo can undergo hundreds of hours of vibration. This makes any 1:1 mapping of field time into laboratory test time impractical. By applying Minor's rule for cumulative fatigue damage, D, along with the PDFs to the problem it becomes possible to "collapse" the underlying field service life down to a much more tractable laboratory test. The formula for Minor's rule is shown in Eq. (2).

$$D = G^{a}T \qquad (2)$$

Where G is the acceleration level, 'a' is the fatigue scaling exponent for the material of interest, and T is he duration of the fatigue event.

For the case where the acceleration level is not constant, Minor's rule states that the cumulative fatigue damage can be treated as the summation of the fatigue damage incurred at each discrete excitation level. The formula in Eq. (3) is an expression for the cumulative fatigue damage, D, with the variations in field response level represented by the PDF, P(n).

$$D = T_f \sum_{n=1}^{m} G(n)^a P(n) \qquad (3)$$

Where G(n) is the g_{rms} corresponding to the nth segment of the PDF and T_f is the field service lifetime.

Since the total damage can also be related to the laboratory test level, G_{lab}, and duration, T_{lab}, using Minor's rule, one can relate the laboratory test to the field environment for the trailer using the formula in Eq. (4).

$$(G_{lab})^a T_{lab} = T_f \sum_{n=1}^{m} G(n)^a P(n) \qquad (4)$$

This relationship makes it simple to estimate the test duration for a given laboratory test level needed to produce the same fatigue damage as is expected in the field. Of course, the most logical initial choice for the laboratory test level is a straight line approximation of the worst case Moriarty PSD envelope (whose g_{rms} can be defined to be g_{mor}). This ensures that any component being tested in the laboratory is not being subjected to higher levels than is would see at some time in the field. Assuming a fatigue scale factor of 3 dB/decade (a=6.64), it was possible to define a laboratory test time that was 1.1% of the original field service life for Interstate highways and 1.7% of the original field service life for rural highways. The Moriarty PSD envelope was assumed to exist 100% of the time for that portion of the service life spent on city streets and dirt roads.

This reduction was still not enough to produce a practical laboratory test (due primarily to the conservative treatment of the city street and dirt road environments). Therefore, it was necessary to raise the test level an additional 8 dB in order to achieve an acceptable test time. However, while the final test level was higher than anything the trailer could ever expect to see, it was much less than it might have been if not for the initial reduction in the test time made possible by the use of the Interstate and rural highway PDFs.

WORST CASE SHOCK MEASUREMENT (MORIARTY TRIP)

Fourteen (14) shock events were analyzed from the Moriarty trip for the purpose of establishing the maximum shock for the Moriarty road course. The 100 worst shocks were recorded during the DC road trip. Figure 3 presents a comparison of the worst case SRS envelopes of the Moriarty and DC road trip shocks (denoted mor env... and dc int env... respectively). The difference in the two SRS for frequencies below 5 Hz is due to the fact that the Moriarty DAS could not measure response below 5 Hz while the DC DAS could.

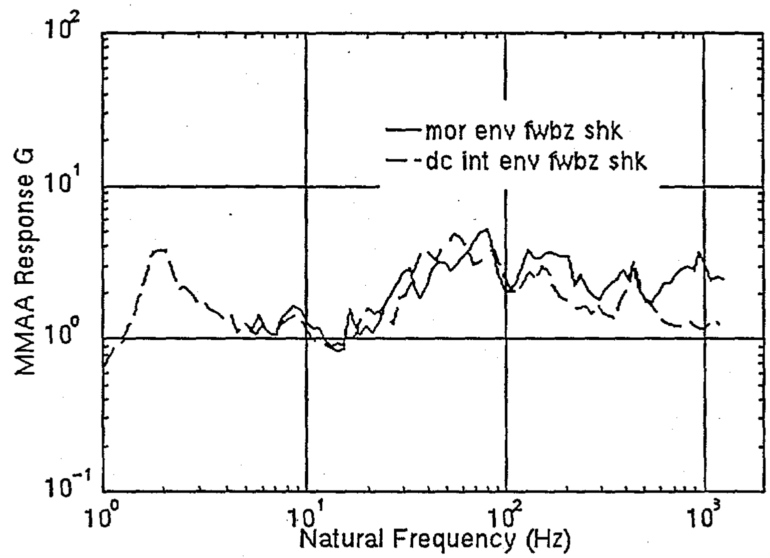

Figure 3: Maximum Shock Responses for Moriarty and DC Road Trips

STATISTICAL SHOCK MEASUREMENT (DC TRIP)

The data recorder used for the DC return trip recorded the 100 highest shocks (based on the measured peak g values). This technique is an excellent way to capture the most severe shock inputs for the trailer without having to record and analyze hours of analog data. However, by the very nature of the recording scheme we did not record a full, unbiased ensemble of shock responses (no shocks with a peak g value below 0.5 g's were saved since the EDR-3 memory was filled up with shocks of greater than 0.5 g's. In short, we only had the upper portion of the database.

Therefore, it was necessary to "fit" the histogram of the DC shock data, h(x), to a PDF, p(x), of known shape and then draw the statistical significant of the DC shock data from that PDF. The histogram was computed using bins that aligned with the DAS quantization bins. The lowest bin was deleted from the database since it was assumed to be underpopulated due to the 100 event limit on the database (it only contained 5 data points). It was also necessary to 'normalize' the histogram in order to permit a direct comparison with the PDF. The normalized histogram, $h_n(x)$, was computed using the formula shown in Eq. (5).

$$h_n(x) = \left\{ \frac{h(x)}{N\Delta x} \right\} \left[\frac{p(x_{min} < x < x_{max})}{p(x)} \right] \qquad (5)$$

Where N is the size of x, and Δx is the width of the bins in the histogram. The expression in the [] is used to adjust N up to the presumed number of shocks that would have been measured with an unbiased measurement scheme.

A parametric study was performed to fit the normalized histogram to a PDF for lognormal and exponential distributions. In the end, it was determined that the exponential distribution, for which the formula is shown in Eq. (6), produced the best fit for the data.

$$p_{exp}(x) = \frac{1}{m} \exp\left[- \frac{x}{m} \right] \qquad (6)$$

Where x is the ensemble of peak g values and m is the mean of x (the final best fit value for the mean was determined to be m=0.125).

Figure 4 presents a comparison of the normalized histogram for the DC shock data (designated as dc int hist...) with the final "best" fit PDF (designated as dc int pdf...). The seemingly low level of the leftmost histogram bin is assumed to be a sign that even that bin is underpopulated.

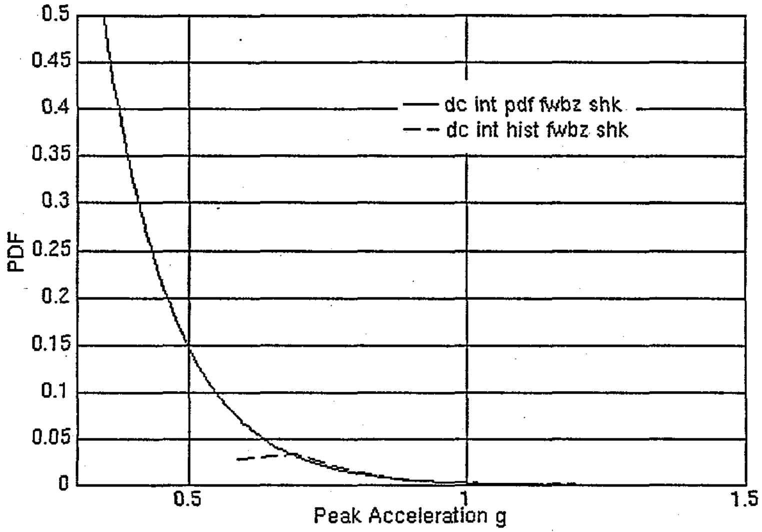

Figure 4: Comparison of Probability Density Function and Histogram for the DC Shock Database

Figure 5 presents the PDF of the DC shock data (denoted dc int pdf...) along with the peak g value for the worst case (maximum g) shock event measured during the DC trip (denoted dc int max...). The ideal peak g value to use with this figure is the peak value measured during the Moriarty trip. Unfortunately, that peak g value was not saved from the initial data reduction effort. However, because the Moriarty SRS envelope is comparable to the DC SRS envelope, the peak g values are also assumed to be comparable.

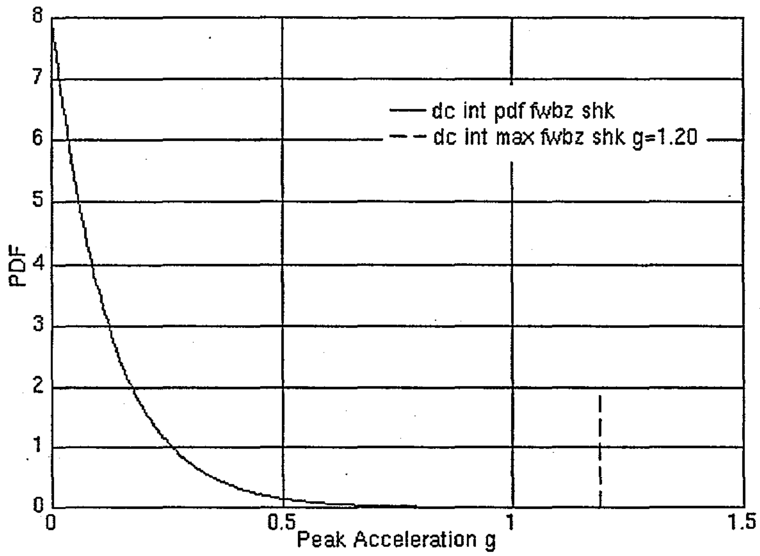

Figure 5: Probability Density Functions for DC Shock Database

SUMMARY OF SHOCK RESULTS

As was the case for the vibration databases, a probability of occurrence and confidence interval were computed for the Moriarty SRS envelope using the data for the DC shock database (100 events). The DFL was also used for this exercise and the results showed that the Moriarty SRS envelope exceeds the expected shock response level 99% of the time for Interstate highways with at least a 63% confidence interval (P99/63).

However, it is important to note that the lack of statistically significant shock data for the other road types of interest presents a major gap in the overall database.

CONCLUSIONS

There is no argument that a cross country road trip consisting of long stretches of every representative road type of interest using a heavily instrumented trailer represents the ideal test series. However, the combination of the high channel count (31 channels) short duration road test and the small channel count (3 channels) cross country trip does provide a degree of statistical confidence in the envelopes of the short trip data with significantly less overall effort.

It is believed that the results for the DC Interstate and Moriarty rural highway vibration environments represent sound statistical analyses. The need to restrict the probability prediction for the rural highway response levels was due in large part to the fact that this test was added as an afterthought using the limited data available from the short trip DAS. A significant improvement could have been achieved if we had been able to use the EDR-3 DAS for that trip as well.

The DC shock database is a valid representation for Interstate highways and therefore provides assurances that the Moriarty shock data are acceptably conservative with respect to that road type. However, intuition would suggest that since the peak Moriarty shock response was comparable to the peak DC Interstate shock response, the Moriarty data will not provide adequate margin for the other road types (which are traditionally less well maintained compared to Interstate highways).

This fact caught us somewhat by surprise since it was relatively easy to be sure that we hit every pothole, expansion joint, and railroad crossing on the Moriarty road course. The only explanation we can come up with is the fact that we were not allowed to conduct any tests that might damage the trailer (which ruled out running over things such as curbs or roadkill). It is interesting to note that while similar tests conducted in the past by Sandia did not attempt to record volumes of response data, they did conduct contrived shock tests (which probably gave them a better worst case shock level than we achieved during this test series). Therefore, as a result of lessons learned from this test series we will make a strong case in future test series for either being allowed to conduct one or two contrived shock tests even if they do pose some risk to the test article or being allowed to conduct statistically significant shock tests on all road types of interest.

REFERENCES

[1] Silverman, B. W., *Density Estimation for Statistics and Data Analysis* (Chapman and Hall, London, UK, 1986), Using a Gaussian Kernal, p65.
[2] Piersol, A. G., "Determination of Maximum Structural Responses From Predictions or Measurements at Selected Points," 65th Shock & Vibration Symposium; October 31-November 3, 1994, Vol I, pp118-131.