2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

INVESTIGATION OF THE DURABILITY TRANSFER CONCEPT FOR VEHICLE PROGNOSTIC APPLICATIONS

Andrew Halfpenny, PhD
HBM – nCode Products
Southfield, MI

Shabbir Hussain
US Army TARDEC
Warren, MI

Scott McDougall
Mark Pompetzki, PhD
HBM – nCode Products
Southfield, MI

ABSTRACT

Vehicle prognostics are used to estimate the remaining useful life of components or subsystems, based on a limited number of measured vehicle parameters. Ideally, sensors would be available for every component and failure mode of interest, such that accurate data could be measured and used in prognostic estimates. However, this is impractical in terms of the number of sensors required and the costs to install such a system and maintain its integrity. A better solution is to relate the loading on a specific component to more generic vehicle behavior. This paper reviews a methodology referred to as the "Durability Transfer Concept", which suggests that damage, or severity of usage, at various points of interest on a vehicle can be predicted simply from measured accelerations at some nominal location – a wheel axle, for example. Measured accelerations are double integrated to get displacements. Those displacements are then filtered using the Rupp or Lalanne method. A transfer function is devised that relates nominal displacements to local damage on critical components. The results show good correlation between measured acceleration on a vehicle and damage at a remote location. However, correlation does depend on coherence; therefore, it is important to select representative locations for the accelerometers relative to the critical components. For best results, the transfer function requires a good range of usage conditions – i.e., representative terrain roughness, speed profile and vehicle weight conditions. In conclusion, the Durability Transfer Concept offers a good solution for predicting severity of usage for structural components on a vehicle, including chassis, steering and suspension components. The Rupp filtering method is preferable in this case where damage is attributable to low frequency terrain induced fatigue.

INTRODUCTION

This effort strives to corroborate the Durability Transfer Concept [1] for calculating severity of usage in military wheeled vehicles. The Durability Transfer Concept suggests that damage, or severity of usage, at various points of interest on a vehicle can be predicted simply from measured accelerations at some nominal location – a wheel axle, for example. This paper explains the Durability Transfer Concept in some detail. A comparison between the Rupp and Lalanne [4] filtering methods, including pros and cons, is provided. Next, we describe the software platform created to evaluate the two methods. This software platform is a combination of commercial off-the-shelf (COTS) signal processing and math calculation tools. Lastly, 240 datasets from proving ground tests on two HMMWVs (figures 1 and 2) are used in various combinations to test the validity and robustness of the two methods.

HMMWV M1151P1

Curb Wt. = 10,350 lb GVW = 12,100 lb

Figure 1: Comparable to test vehicle 1151

Vehicle used to generate dataset 1152
(HMMWV M1152):

Curb Wt. = 6,400 lb GVW = 11,500 lb

Figure 2: Test vehicle 1152

Our experiments show the possibility for good correlation between measured acceleration on a vehicle and damage at a remote location. However, that correlation diminishes as coherence diminishes. Therefore, it is important to select representative locations for the accelerometers relative to the critical components. For best results, the transfer function requires a good range of usage conditions – i.e., representative terrain roughness, speed profile and vehicle weight conditions. The Durability Transfer Concept and Rupp filtering method offer a good solution for low frequency terrain induced fatigue, whereas Lalanne offers a better solution for higher frequency resonance induced failures.

THE ANALYSIS PROCESS

The analysis process is divided into three steps:

Step 1:

- Acceleration and strain measurements are recorded on a vehicle as it traverses the proving ground. In order to obtain a good statistical representation of all the terrain conditions, several measurements are taken under a range of speeds and vehicle loading conditions.
- Acceleration time histories are measured on the vehicle at “nominal” locations. These data are representative of the general loading environment of the vehicle. An analysis of damage vs. frequency is performed using either the Rupp or Lalanne methods. This analysis reduces long time histories into a very compact histogram format which is much more suitable for onboard storage and long-term archival.
- Strain time histories are also recorded simultaneously with the acceleration data. These strain data are recorded on a number of specific components on the vehicle. These are the components we want to monitor for prognostic damage accumulation. A fatigue analysis is run on these strain data in order to find the damage content of each proving ground surface under each weight condition and ground speed.

Step 2:

- Determine the transfer function that relates nominal acceleration to fatigue damage. This is done for each component or area of interest.

Step 3:

- Calibrate the theoretical “damage correlate” to the statistical likelihood of real component failure, or alternatively to the certified component life.

Details of these three steps follow next.

Step 1 – Calculating damage vs. frequency histograms from acceleration time histories

Time histories of acceleration are recorded at a number of “nominal” locations on the vehicle. These data are representative of the general loading conditions on the vehicle under a range of terrain, ground speed and weight conditions.

Damage and frequency are both important because different components will be more or less sensitive to different frequencies of loading. This is due to resonance in the components and the fact that damage decays exponentially with frequency. Loading frequency is dependent on the terrain profile and the speed the vehicle is travelling.

It is necessary to reduce these long acceleration time histories into a compact histogram format that retains the desired attributes: i.e. damage content and frequency. These compact spectra are easier to store onboard the vehicle and are also easier to archive for future use.

Two methods have been identified which are potentially suitable for this type of analysis:

1. Rupp Damage Spectrum
2. Lalanne Fatigue Damage Spectrum (FDS)

Both methods are very similar in their implementation and involve the following steps:

1. Filter the measured time signal of acceleration to extract the desired frequency band.
2. Calculate the damage content of the filtered signal using a traditional stress-life (SN) approach and using a rainflow cycle counting algorithm.
3. Plot the resulting damage number on the damage vs. frequency plot.
4. Repeat the process choosing a new frequency band until the damage vs. frequency plot is completed over the desired range of frequencies.

The two methods differ only in their choice of filters. The Rupp method opts for a ‘band-pass’ filter whereas the Lalanne method opts for a function based on the response of a single degree of freedom (SDOF) oscillator. This is shown schematically in figure 3.

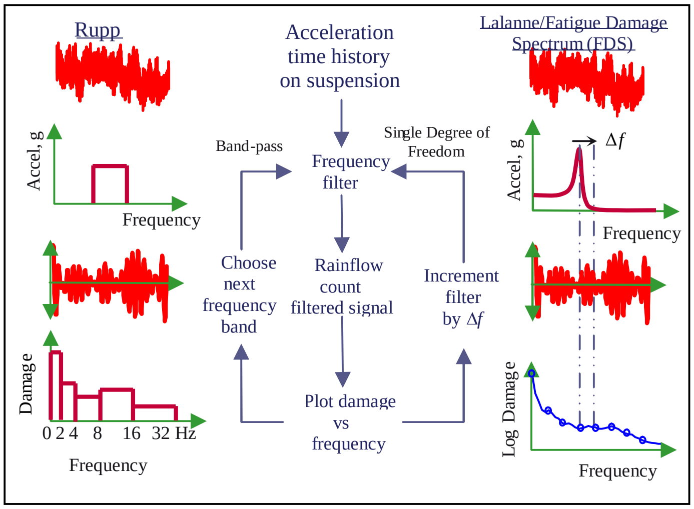


Figure 3: Derive Damage vs Frequency Plot.

Comparison of the Rupp and Lalanne approaches for deriving damage vs. frequency histogram

Rupp uses a band-pass filter in order to select the frequency band of interest in the signal. The bandwidth increases logarithmically over the ranges: 0-2, 2-4, 4-8, 8-16, 16-32Hz. It is generally appropriate to consider up to 32Hz for terrain induced loading on a vehicle fitted with pneumatic tires such as trucks. Higher frequencies may be required for other types of ground vehicle; for example, tracked vehicles and vehicles with prominent tread patterns such as tractors.

Lalanne uses a filter function based on the response of a single degree of freedom (SDOF) system. This function is more representative of the resonant response of a component and allows more precise control of frequency selection than the Rupp method.

Rupp returns a histogram of logarithmically increasing frequency bands. Over the range 0-32 Hz, it occupies only 5 frequency bands and provides an efficient solution for terrain-induced loading over a low frequency range.

Lalanne offers precise control of the frequency and is more suitable to narrow-banded vibration arising from engine and transmission-induced effects or resonant response of critical high-value equipment.

Advantages and disadvantages of each method

Rupp offers an efficient approach for low frequency ground-induced vibration. It offers acceptable performance over the low frequency range using only 5-6 histogram bins. Over the same frequency range (0-32Hz), Lalanne will require many more calculation points (typically 32) to provide the same level of accuracy.

At higher frequencies, the Rupp approach offers poor frequency resolution and is surpassed in all aspects by Lalanne. Even if the Rupp filter bandwidth was reduced, the filter is more prone to ringing and does not model the response to resonance as closely as Lalanne.

The precise nature of Lalanne's frequency selection function offers significant advantages when analysing the effects of resonance at higher frequencies such as transmission-induced effects or specific effects on critical high-value equipment such as optical and electronic components, where the filter may be tuned with precision.

The Rupp approach is better suited for quasi-static components under low frequency loading – such as ground vehicle suspension, steering and chassis members.

Step 2 – The Transfer Function

The transfer function is used to transform measured acceleration values, which are measured at some "nominal" locations on the vehicle, into fatigue damage at the critical locations.

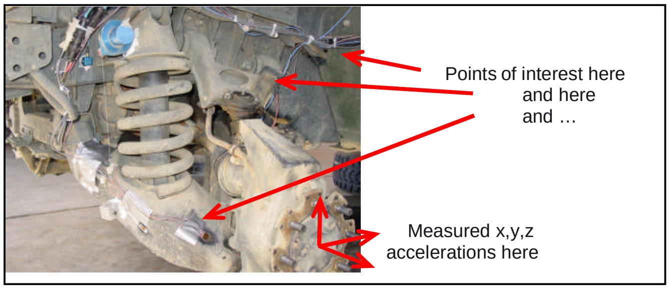


Figure 4: Acceleration at nominal location.

It is often impractical to measure damage directly at the critical components on every service vehicle and so this inferred approach offers an efficient, pragmatic and elegant solution.

The transfer function is derived using proving ground measurements where "nominal" acceleration is measured along with local strain on the critical components. Many "nominal" locations may be used in the transfer function. The best results are obtained for nominal locations that exhibit strong coherence with the critical locations. Engineering judgement or a more sophisticated coherence analysis is used to determine these sites. The transfer function analysis itself will also reveal any non-participating input channels.

Acceleration at the nominal locations will be measured on all service vehicles – this is a known quantity. The acceleration time signals are converted to a histogram of fatigue vs. frequency using either the Rupp or Lalanne approach, depending on which offers the preferred advantages (see previous discussion). We will refer to this spectrum as the Relative Damage Spectrum (RDS). A transfer function is then required to transform the RDS into damage at the critical locations.

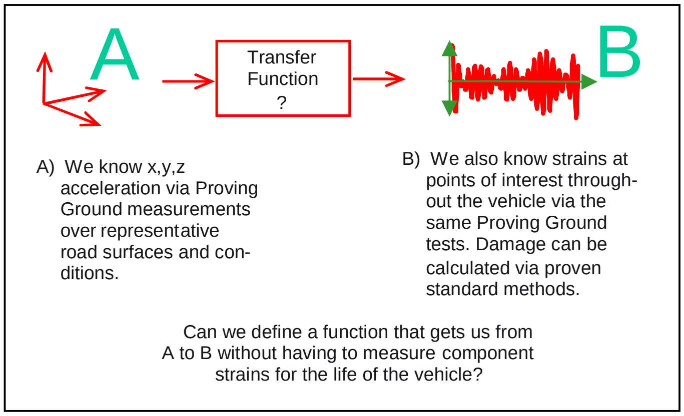


Figure 5: The required transfer function.

The transfer function is obtainable from analysis of measured acceleration at the nominal locations along with measured strain at the critical locations. Strain measurements are only required for deriving the transfer function; strain measurements will not be required on vehicles in the field.

Calculating the Transfer Function

This discussion assumes that we are using the Rupp fatigue histogram over 5 frequency bands (0-2, 2-4, 4-8, 8-16 and 16-32Hz). Therefore, 5 fatigue coefficients, or "correlates," are generated for each accelerometer channel. For each proving ground event, a single damage value is calculated at the critical location along with the five damage correlates for each acceleration channel. If tri-axial accelerometers are used then 15 damage correlates are recorded at the "nominal" location (5 damage correlates for each direction). See figure 6a.

In order to obtain a transfer function of 15 coefficients (one for each damage correlate), it is therefore necessary to record at least 15 proving ground runs. This yields 15 equations with 15 unknowns (the 15 transfer coefficients.) See figure 6b. Another 5 coefficients must be calculated for every additional accelerometer channel used.

Theoretically, the transfer coefficients (column vector C) can be found using linear matrix inversion based on the 15x15 matrix of damage correlates (RDS) and the 15 damage values (D) recorded during the 15 proving ground events. However, difficulties such as matrix ill-conditioning (through an inappropriate choice of events), and a desire to use more than 15 data sets, makes other solutions more appropriate. These are discussed below.

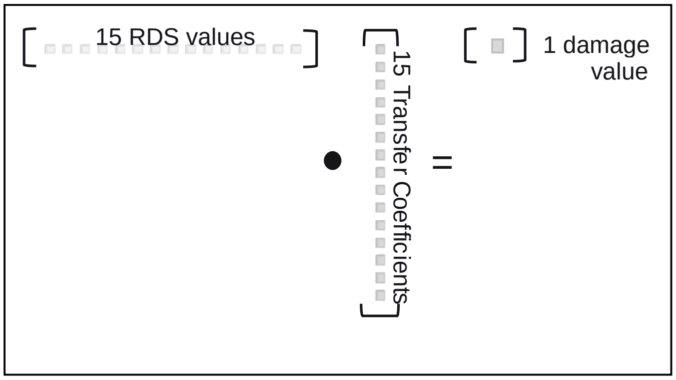


Figure 6a: The transfer function – 1 eq., 15 unknowns.

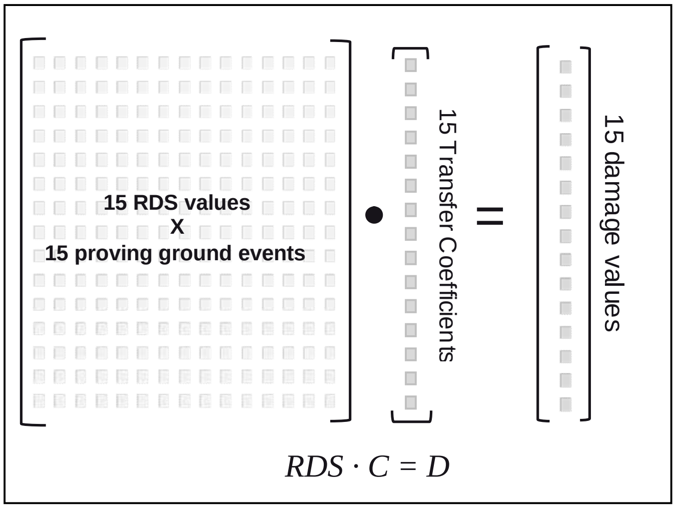


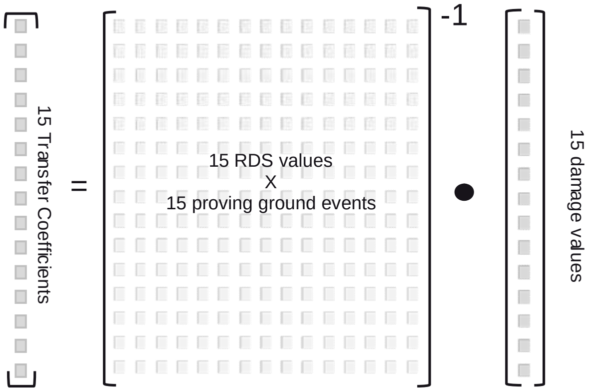
Figure 6b: The transfer function – 15 eq., 15 unknowns.

Linear matrix inversion proves inadequate for this analysis for the following reasons:

1. Prone to ill-conditioning errors – this occurs most often when the input accelerations do not fully account for the damage content at the critical strain channel.
2. Returns negative transfer coefficients which leads to negative fatigue damage contribution which is a physical impossibility.
3. Must be a square matrix; i.e., must have exactly the same number of proving ground events as unknown transfer coefficients.

A better approach to solving this matrix equation is based on non-linear optimization. An iteration algorithm is used to estimate the transfer coefficients and then calculate the resultant damage. This is then compared with the recorded damage and the coefficients are iterated until convergence is obtained. The optimization can be based on a neural network solution or classical algorithms such as nonlinear simplex, quasi-Newton, etc. A quasi-Newton optimization algorithm is used in this case study. This approach also requires a function to be defined on which to assess the extent of the convergence: this is known as the ‘error function’. In this project the ‘error function’ is defined as the sum of the square of the deviation of the log of measured damage from the log of calculated damage.

Solution 1 – linear matrix inversion: $C = RDS^{-1} \cdot D$



Solution 2 – nonlinear optimization that minimizes an error function

Given $RDS \cdot C = D$
and $C \geq 0$
and $err(C) = \sum \{\log(RDS \cdot C) - \log(D)\}^2$

Optimize to find C based on minimizing error function

Figure 7: Solution options for the matrix equation

It is important to consider an adequate mix of proving ground surfaces, vehicle weight conditions and vehicle speed to ensure sufficient coverage of the entire range of terrain, frequency and amplitude levels. The non-linear optimization approach facilitates solving an ‘over-resolved’ matrix: i.e. 15 RDS columns with more than 15 RDS rows (proving ground events.) There must be at least 15 proving ground events to calculate the 15 transfer coefficients but more can be used if available and the result will be statistically better.

Step 3 – Validating the Transfer Function

The optimization algorithm will always yield a result for the transfer function because it only looks for convergence of the error function. Therefore a validation study is necessary to determine the quality of that convergence.

The first indicator of quality is the final error value calculated in the convergence analysis. A high error indicates poor performance. The engineer should then inspect the transfer coefficients and observe coefficients with relatively low amplitudes. A coefficient tending to zero indicates that this particular correlate (acceleration channel and frequency band) contributes little to the overall damage. Conversely, high amplitude coefficients imply significant contribution to damage. In figure 8, three correlates are seen to be significant in column vector C, as indicated by the math calculation tool’s coloring scheme. The most dominant is the transverse (y) acceleration over the frequency ranges 2-4 and 4-8Hz, along with the longitudinal (x) acceleration over the frequency range 2-4Hz. (Note that the acceleration channels are listed as vertical, transverse and longitudinal or z, y, x – not x, y, z.)

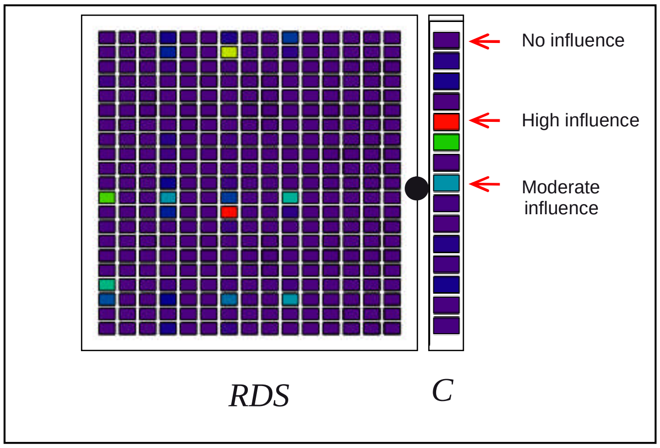


Figure 8: Evaluating the transfer function

Engineering judgement is useful in explaining whether the predicted trends make sense. In this case, the critical location is on the front tie rod, so lateral acceleration levels will have the most significant effect on damage at this location. A more sophisticated coherence analysis can also be used to verify cases of low and high coherence between acceleration channels and damage. This is discussed beginning on page 7.

The optimization solution can also be sensitive to the initial estimate of the results. The user must specify an initial vector of transfer coefficients. The optimization algorithm uses this as a starting point in the iterative solution.

In this project all coefficients were initially set to the same value: i.e. assume all channels offer equal contribution. The convergence was found to be reliable on this basis; however, it was found to be sensitive to the value chosen. For example, all coefficients set to unity often returned an error "not converged"; whereas, reliable convergence was found when all coefficients were set to 1000.

CONFIGURATION OF THE EXPERIMENT

A computer workbench has been built using commercial off-the-shelf (COTS) signal processing and math calculation tools. The signal processing portion is broken into two pieces (referred to as flows), one at the beginning and one at the end, and the math calculation portion sits in the middle. The analysis process looks like this:

1. Proving Ground Analysis flow
    - Takes the measured acceleration data and computes the Rupp Relative Damage Spectrum (RDS)
    - Simultaneously takes the measured strain data and computes the damage value for each proving ground dataset
    - Outputs RDS matrix and damage vector
2. Transfer Function Solution
   Takes the RDS matrix and the damage vector from the Proving Ground Analysis flow and computes the transfer function between acceleration input at the nominal locations and fatigue damage at the critical location.
3. GlyphWorks Damage Filtering flow
   Takes any input of acceleration and applies the transfer function derived in the Transfer Function Solution to obtain the predicted fatigue damage at the component. This flow also computes the fatigue damage at the same critical location using the measured strain data so the quality of prediction can be validated

Experiment Step 1 – Derive Damage vs. Frequency Plot

The Proving Ground Analysis flow inputs proving ground measurements from several tests. It calculates the RDS matrix for all frequency bands in the range 0-32Hz for accelerometer channels chosen by the user. It also calculates the fatigue damage based on a single nominated strain channel.

The acceleration channels are double integrated to obtain displacements. Fatigue damage is proportional to relative displacement and not acceleration so this offers better damage convergence than using acceleration directly. Before integrating, the flow performs a high pass filter (0.5Hz) to remove DC offsets which lead to erroneous integration results.

The displacement signal is then filtered using 5 frequency bands (0-2Hz, 2-4Hz, 4-8Hz, 8-16Hz, and 16-32Hz). The final filtered displacement signals are combined into a single test with the following channel sequence:

Test 1 / Chan1 (z, vertical) (0-2Hz)
Test 1 / Chan2 (y, lateral) (0-2Hz)
Test 1 / Chan3 (x, fore-aft) (0-2Hz)
Test 1 / Chan1 (z, vertical) (2-4Hz)
Test 1 / Chan2 (y, lateral) (2-4Hz)
… etc …
Test 2 / Chan1 (z, vertical) (0-2Hz)
Test 2 / Chan2 (y, lateral) (0-2Hz)
… etc …

Fatigue weighting is performed for each channel based on a simple Wöhler (SN) curve with a slope (b) of 4. This is typical of fatigue failure adjacent to notches and welds. The y-intercept of the SN curve is not required for relative comparisons and this is set to unity in this experiment.

The selected strain channel is processed simultaneously. It is first converted to stress by multiplying by the modulus of elasticity, and the damage is then derived in a similar manner. [1]

Experiment Step 2 – Calculate the Transfer Function

A COTS math tool is used to calculate the coefficients of the transfer function. The RDS and local damage vectors that were calculated in the previous step become the input to the math tool. The transfer function is derived using the tool's 'Minimize' function which is set to "Quasi-Newton.' The error function is defined as the sum of the square of the deviation between log damage predicted and log damage recorded from the proving ground data. An indication of quality is shown in the graphs below. An error in damage prediction within a factor of ±3 (33% to 300%) is generally considered good on the training data.

---

[1] Some of the measured strain data contained high amplitude spikes. An additional spike detection algorithm was inserted in the flow to filter these spurious data. The algorithm was configured using a 'Statistical' detection method with a 4 standard deviation threshold and a 5% gate.

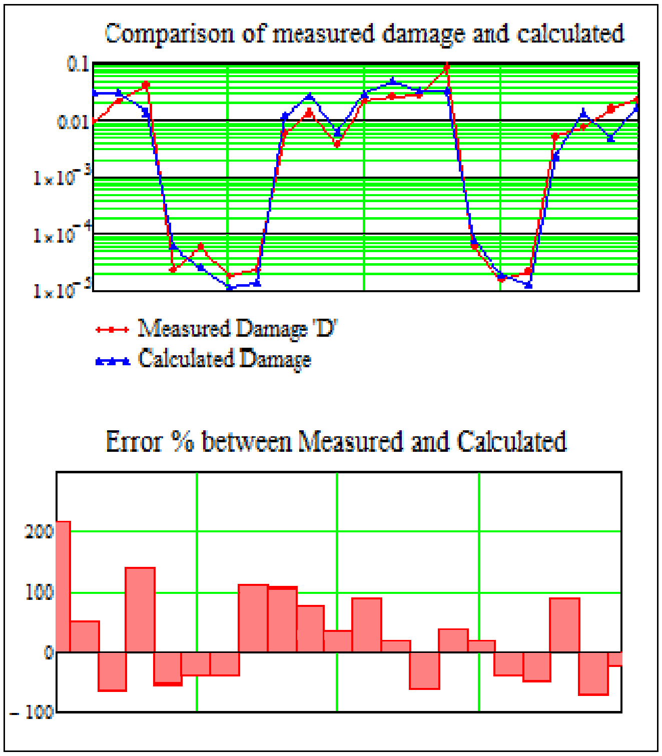


Figure 9: Error plots of damage

Experiment Step 3 – Validation of the Transfer Function

The Damage Filtering flow takes inputs of acceleration at the nominal locations on the vehicle and strain at the identified critical component. The input time series (proving ground events) are concatenated together to form a single measurement that is representative of a long period of real usage. This choice of proving ground data should be independent of those used for the initial transfer function calculation where possible.

The flow calculates the RDS matrix for the concatenated acceleration channels and transforms this into damage at the critical location using the transfer function input from the math calculation tool. The flow also calculates the damage at the critical location directly using the concatenated strain data for the critical component. The actual damage can then be compared with the predicted damage.

If the ratio of the predicted damage to the actual damage is within a factor of 2 (0.5 to 2.0) then the results are excellent, a factor of 3 (0.3 to 3.0) then the results are good, and within a factor of 10 (0.1 to 10) are considered tolerable for fatigue damage purposes. This is explained more fully on page 9.

EXPERIMENTS AND RESULTS

A number of experiments were constructed using proving ground data from the two HMMWV test vehicles described in the Introduction. Within each experiment, multiple tests were run using various combinations of vehicle weight, road surface, speed, etc. in an attempt to prove or disprove each experiment's premise. We'll first discuss the baseline experiments (1-5) in a general sense. Then we'll discuss coherence and convergence. Finally, each individual experiment's parameters and results are listed. These are summarized in table 1 on pages 13-14.

Overview of Experiments 1- 5

These experiments consider an ideal case where the measured nominal acceleration channels are located adjacent to the critical component. This provides the optimum coherence between input and response and should give an indication of the best-case usage of this method

Experiments are based on datasets from 2 HMMWV variants - 1151 and 1152 - and consider x,y,z acceleration measured at the left front wheel center. Damage is recorded using strain channel 40 pertaining to the left tie rod end. The tie rod forces are coherent with the wheel center accelerations so this location has been chosen to represent the best example of correlation from the method.

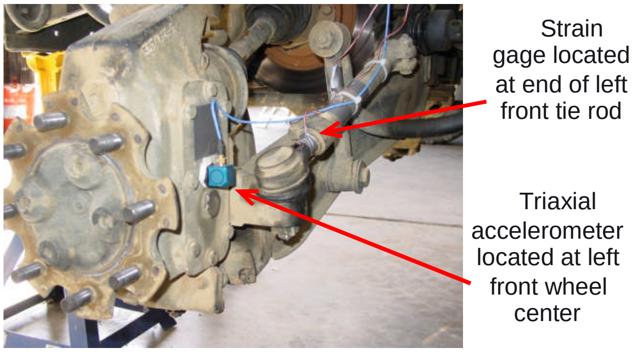


Figure 10: Data collection locations

The transfer function is derived using samples of all the proving ground surfaces from dataset 1151 and includes the entire range of vehicle speed from 15 – 88mph. Speed is important because frequency increases in proportion to speed. All measurements are recorded under curb weight loading conditions.

Frequency and coherence analysis between input acceleration and strain response

Figure 11 shows PSDs of the three input acceleration channels (vertical, transverse and longitudinal) and the strain response at the tie rod end, all at the left front corner of the vehicle. The analysis was performed on data measured over the 'Paved' proving ground surface under curb weight conditions at a speed of 40mph.

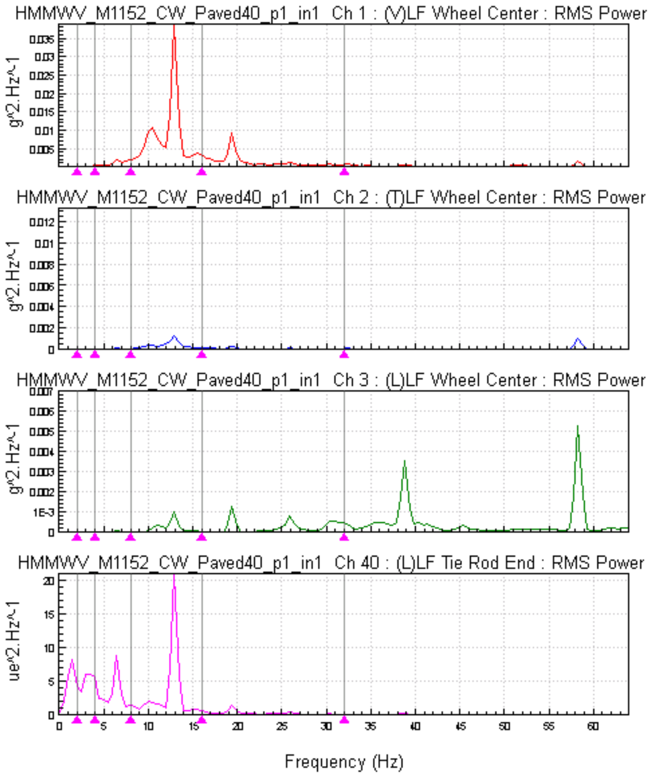


Figure 11: PSD of Input and Response Channels – Paved @ 40mph

The most significant vibration input occurs at approximately 13Hz which corresponds with the 'wheel hop' frequency (first suspension spring mode.) The strain signal also demonstrates lower frequency response attributable to other modes such as the vehicle pitching mode, etc. The higher frequency peaks seen in the longitudinal acceleration channel correspond to harmonics of this particular proving ground surface and the speed of the vehicle (Paved at 40mph).

The coherence between each input and the response is shown in figure 12. A coherence of zero implies that the strain response has no correlation with the input acceleration measurements; whereas, a coherence of 1.0 implies that the strain response is directly attributable to that particular acceleration input channel. In most cases the strain response will depend on a mixture of all the input channels. In this plot the contribution of all 3 input channels is very significant as values are much greater than zero. The coherence will vary with respect to frequency as some modes in one channel dominate the strain response. Considering the frequency ranges of interest (0-2, 2-4, 4-8, 8-16, 16-32Hz as shown by the vertical lines in the graphs) one or more of the measured channels are seen to have significant coherence with the strain response. This implies that using these channels in the analysis should yield a well correlated prediction of the damaging load levels without having to consider other input channels as well. This analysis backs up what engineering judgement already tells us.

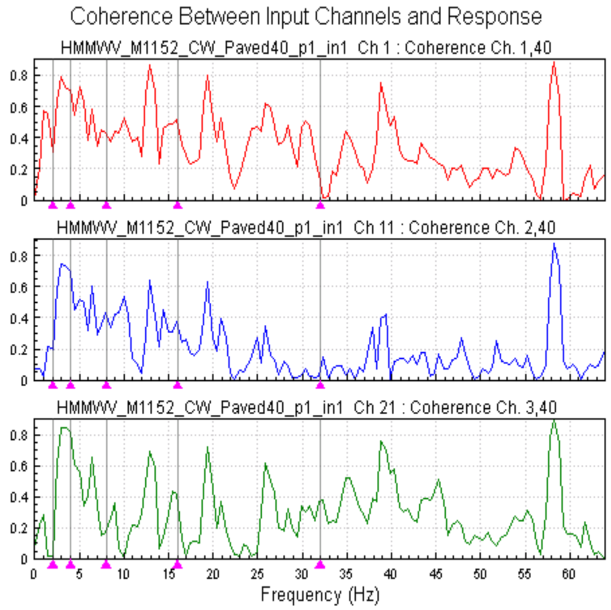


Figure 12: Coherence between Input and Response - Paved @ 40mph

Coherence was also checked for data measured over the 'Gravel" proving ground surface under curb weight conditions at a speed of 35mph. The most significant vibration input again occurs at approximately 13Hz which corresponds with the 'wheel hop' frequency (first suspension spring mode.) The strain response shows significant energy up to approximately 20Hz. The proposed analysis range (0-32Hz) is therefore acceptable.

The longitudinal acceleration response includes contributions up to approximately 45Hz. These are attributable to the gravel surface and the relatively high ground speed. However, these are much less significant than the vertical input and therefore, contribute little to the strain response at the tie rod end. See figures 13 and 14.

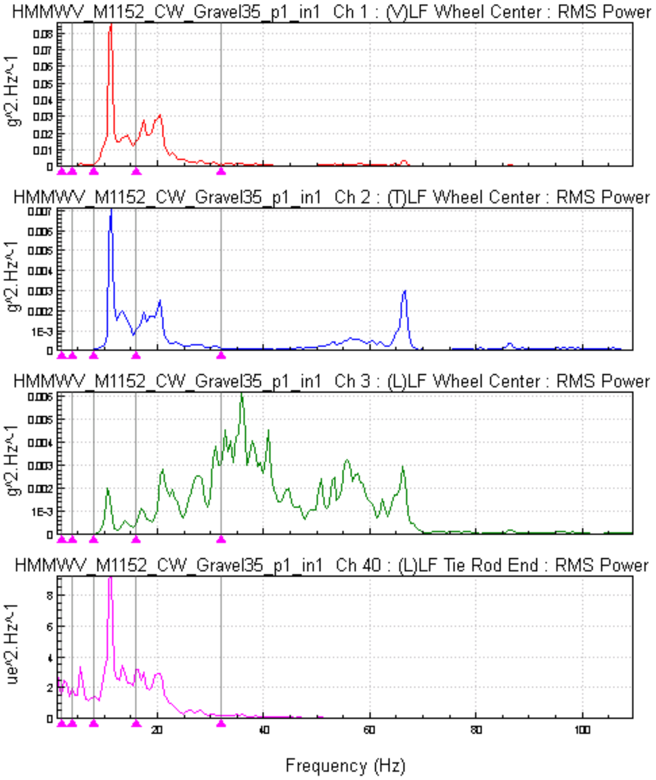


Figure 13: PSD of Input and Response Channels – Gravel @ 35mph

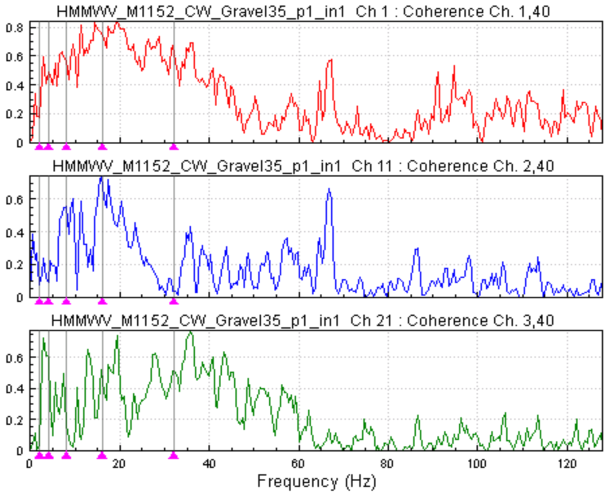


Figure 14: Coherence between Input and Response - Gravel @ 35mph

Convergence check on transfer function

A convergence check on the transfer function (C in figure 15) shows a good spread of contributions from several correlates implying that damage arises as a result of all 3 input acceleration channels over the entire frequency range 0-32Hz. The maximum convergence error of 3.761 is tolerable as it is within an order of magnitude on damage but is greater than a factor of 3. The mean convergence is excellent with a value of 1.41. The convergence check is based on the ratio of the predicted damage (using the generated correlates) to the actual measured damage D. In most cases the optimization-based solution cannot give perfect results for all cases but tries to offer an averaged fit. The convergence check therefore represents how well the generated correlates fit the actual data.

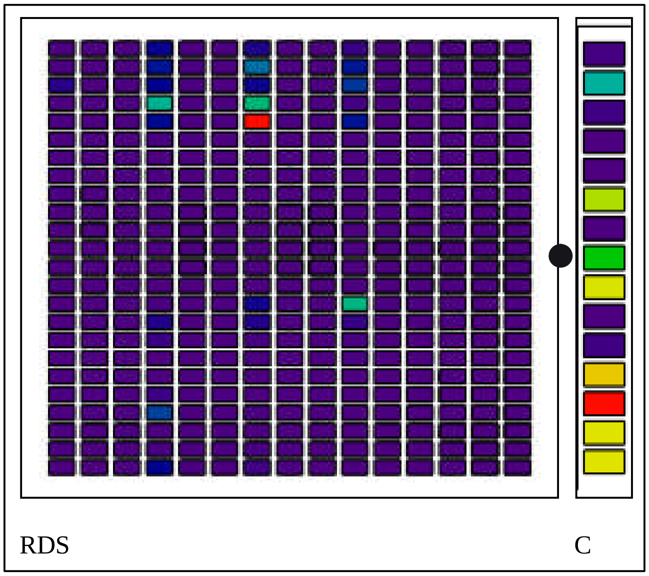


Figure 15: Convergence check of transfer function for experiments 1-5

Definition of 'Good' convergence on fatigue damage prediction

Fatigue crack growth starts at a microscopic level within a component. Even though two components may look exactly the same, originate from the same material batch and derive from the same production line, they will have significant differences at a microscopic level. These microscopic differences result in significant variability in fatigue life. A factor of 2 in fatigue life is very common with simple laboratory specimens and can increase to a factor of 3 or more in more complex machinery. The accuracy of prognostic prediction cannot exceed the physical limitations of nature. It is therefore unreasonable to try and derive methods which offer greater accuracy than a factor of 2-3 on life or damage prediction. Many structural health experts tolerate errors up to a factor of 10 in complicated systems. The benefits of prognostic analysis are not in identifying specific failures but rather in ascertaining the severity of vehicle usage, deployment and reliability to ensure that condition-based maintenance scheduling is facilitated.

EXPERIMENT 1

Exp. 1 Objective

Demonstrate the accuracy of predicted damage values vs. measured damage values over a range of randomly selected samples of data. All comparisons are made under curb weight conditions as used in the transfer function derivation.

Exp. 1 Method

The transfer function is calculated using a range of proving ground surfaces and ground speeds as described previously. The transfer function is derived from vehicle 1151 under curb weight conditions. The damage is validated using several random proving ground samples. Samples are also taken under curb weight conditions and the samples are concatenated to create a single long event.

- Test #1 considers the same proving ground spectrum as used to derive the transfer function – this represents the ‘best-case’ scenario. It is similar to the convergence test described on the previous page except all the event measurements are now concatenated to form one long event.
- Test #2 and #3 consider random sets of proving ground surfaces taken from dataset 1151 under curb weight conditions.
- Test #4 considers the entire set of samples measured in dataset 1151 under curb weight conditions.
- Test #5 considers a random set of proving ground surfaces from dataset 1152 under curb weight conditions.
- Test #6 considers the entire set of samples measured in dataset 1152 under curb weight conditions.

Exp. 1 Conclusions

The results demonstrate excellent correlation with the measured damage. The maximum error is within a factor of 1.4. Dataset 1152 is consistent with dataset 1151 in terms of damage accumulation rates.

EXPERIMENT 2

Exp. 2 Objective

Demonstrate that the method is tolerant to changes in weight condition. Loading on structural components is proportional to weight on the basis that force = mass * acceleration. The mass will also affect the vehicle’s dynamic response characteristics and change the frequency and acceleration levels recorded. This experiment will determine whether the method can tolerate increases in weight (loading) and maintain good predictions of damage.

Exp. 2 Method

The transfer function is calculated using the measured data described earlier under curb weight conditions. The damage is validated using several random proving ground samples. All samples are taken under gross weight conditions in this experiment. All samples are concatenated to create a single long event.

- Test #1 considers the same spectrum of proving ground surfaces as used to derive the transfer function; however, the transfer function was derived for curb weight loading whereas the verification is performed using gross vehicle weight measurements.
- Test #2 considers a random set of proving ground surfaces taken from dataset 1151 under gross weight.
- Test #3 considers the entire set of samples measured in dataset 1151 under gross weight.
- Test #4 considers a random set of proving ground surfaces taken from dataset 1152 under gross weight.
- Test #5 considers the entire set of samples measured in dataset 1152 under gross weight.

Exp. 2 Conclusion

Some nonlinearity in amplitude scaling is apparent. However, the prediction is still excellent and will improve if gross weight conditions are also included in the transfer function derivation – see Experiment 6.

EXPERIMENT 3

Exp. 3 Objective

Demonstrate typical performance based on a mix of curb weight and gross weight conditions.

Exp. 3 Method

The transfer function is calculated using the measured data described earlier under curb weight conditions. The damage is validated using several random proving ground samples under a random mixture of all weight conditions.

- Test #1 considers a random set of proving ground surfaces taken from dataset 1151.
- Test #2 considers the entire set of proving ground surfaces taken from dataset 1151.
- Test #3 considers a random sample set of proving ground surfaces taken from dataset 1152.
- Test #4 considers the entire set of proving ground surfaces taken from dataset 1152.

Exp. 3 Conclusion

Results demonstrate excellent correlation with the measured damage, even for a different variant of the same vehicle. Maximum error is within a factor of 1.5

EXPERIMENT 4

Exp. 4 Objective

Demonstrate method reliability under a skewed speed profile.

Exp. 4 Method

The transfer function is calculated using the measured data described earlier under curb weight conditions. Damage prediction is validated using a random mix of data under gross weight and curb weight conditions to determine the sensitivity to a skew in speed profile.

- Test #1 considers a skewed speed profile where Belgian, Bump, Church and Gravel are crossed at speeds less than 30mph using dataset 1151.
- Test #2 same as test #1 but using dataset 1152.
- Test #3 considers a skewed speed profile where Paved and Round surfaces are crossed at speeds greater than 30mph using dataset 1151.
- Test #4 same as test #2 but using dataset 1152.

Exp. 4 Conclusion

The final damage ratio shows excellent convergence with the measured damage on the component within a factor of 1.8. A bias in service usage will not adversely affect the reliability of the method provided the transfer function has considered representative cases.

EXPERIMENT 5

Exp. 5 Objective

Demonstrate method reliability under a skewed vibration amplitude and speed profile.

Exp. 5 Method

Transfer function derived as per experiment 1 under curb weight conditions. Damage prediction is validated using a random mix of data under gross weight and curb weight conditions to determine the sensitivity to a skew in vibration amplitude profile.

- Test #1 considers a skewed vibration profile consisting of only Perry and Round surfaces using dataset 1151. These contain the highest amplitude vibration in the high speed range.
- Test #2 same as test #1 but using dataset 1152.
- Test #3 considers a skewed vibration profile consisting of only Belgian and Bump surfaces using dataset 1151. These contain the highest amplitude vibration in the low speed range.
- Test #4 same as test #2 but using dataset 1152.

Exp. 5 Conclusion

Results demonstrate excellent correlation with the measured damage. Maximum error is within a factor of 1.7. A bias in service usage will not adversely affect the reliability of the method provided the transfer function has considered representative cases.

EXPERIMENT 6

Exp. 6 Objective

This experiment demonstrates the improved performance of the method when the transfer function is derived for both curb and gross weight conditions.

Exp. 6 Method

The transfer function is calculated using a range of proving ground surfaces and vehicle speeds. The transfer function is derived under both curb and gross weight conditions for dataset 1151 measurements. The damage is validated using several random proving ground samples concatenated to form a single long event.

- Test #1 considers the same proving ground spectrum as used to derive the transfer function – this represents the ‘best-case’ scenario.
- Test #2 considers the entire set of curb weight samples from dataset 1151.
- Test #3 considers the entire set of gross weight samples from dataset 1151.
- Test #4 considers the entire set of curb weight samples from dataset 1152.
- Test #5 considers the entire set of gross weight samples from dataset 1152.

Exp. 6 Conclusion

Results demonstrate excellent correlation with the measured damage. Maximum error is within a factor of 1.2 Results show better correlation than with experiment 3 where only curb weight data were used in deriving the transfer function.

EXPERIMENT 7

Exp. 7 Objective

This experiment demonstrates the deterioration in performance when a biased speed profile is used to determine the transfer function. In this case only Belgian and Bump surfaces are used to determine the transfer function. These populate only the low frequency bins of the Relative Damage Spectrum.

Exp. 7 Method

The transfer function is calculated using only Belgian and Bump surfaces traversed at less than 30mph. The transfer function is derived for both curb and gross weight conditions. The damage is validated using several random proving ground samples.

- Test #1 considers Belgian, Bump, Church and Gravel under curb weight conditions. These were taken from dataset 1151.
- Test #2 considers Paved and Round (traversed at speeds in excess of 30mph) under curb weight. These were taken from dataset 1151.
- Test #3 considers Belgian, Bump, Church and Gravel under curb weight. These were taken from dataset 1152.
- Test #4 considers Paved and Round (traversed at speeds in excess of 30mph) under curb weight. These were taken from dataset 1152.

Exp. 7 Conclusion

Results demonstrate excellent correlation when validated against similar data (i.e. speed < 30mph). Results show significant drop in accuracy for results containing significant amounts of high speed (high frequency) data. Maximum error is within a factor of 5. The method becomes less reliable when any particular frequency band(s) are not fully utilized in the derivation of the transfer function.

EXPERIMENT 8

Exp. 8 Objective

This experiment addresses the question of possible deterioration in performance when a location with low coherence is used to determine the damage correlates. In this experiment, the left rear wheel is used to determine the acceleration profile while the critical component is located at the left front tie rod. The experiment is important because economic constraints often limit the number of sensors available on the vehicle. This experiment will demonstrate the validity of the hypothesis that damage is proportional to the terrain profile and is therefore relatively independent of the local source of measurement or the dynamic response from that source to the critical component.

Exp. 8 Method

The transfer function is calculated using a range of proving ground surfaces and ground speeds as described in Experiment 6. The transfer function is derived under both curb and gross weight conditions for dataset 1151 measurements. The damage is validated using several random proving ground samples.

- Test #1 considers the same proving ground spectrum as used to derive the transfer function – this represents the ‘best-case’ scenario.
- Test #2 considers the entire set of samples measured in dataset 1151 under curb weight conditions.
- Test #3 considers the entire set of samples measured in dataset 1151 under gross weight conditions.
- Test #4 considers a random set of proving ground surfaces from dataset 1152 under curb weight conditions.
- Test #5 considers the entire set of samples measured in dataset 1152 under curb weight conditions.

Exp. 8 Conclusion

Results show good to excellent correlation. Maximum error is within a factor of 2.2 (compare with 1.2 for experiment 6 where coherence between measurement and damage location is good.) Results demonstrate that a generic terrain sensor can provide satisfactory correlation with local damage.

Test #2 showed a much larger error than any of the previous tests. A closer examination of the input revealed that one of the events had a significant spike in all three acceleration channels at approximately 16 seconds into the signal. See figure 16.

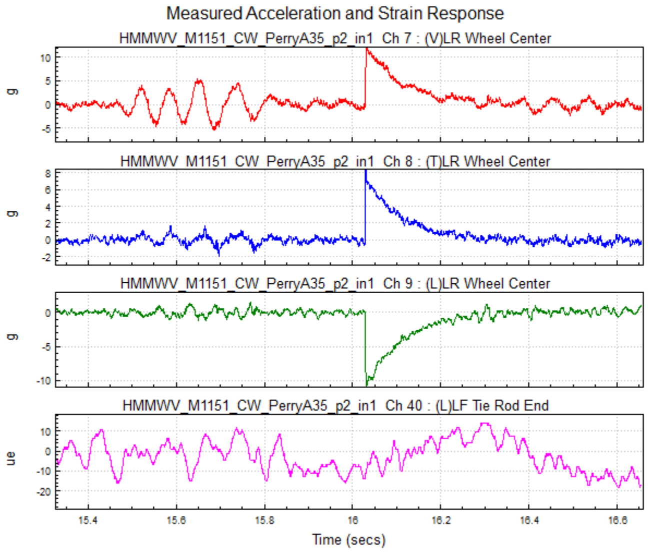


Figure 16: Input anomaly in experiment 8, test 2.

The method is ordinarily tolerant of freak acceleration spikes in the data because damage is determined from the double integral of acceleration. This reduces the significance of short spikes considerably. However, the high amplitude spikes seen here have affected many data points so it is hard to detect whether this is an anomalous event or a highly damaging real event. Furthermore, this type of step function will cause the band-pass filters to ‘ring’ which creates high amplitude anomalous data which leads to high damage accumulation

For this example, the strain channel is available and we can see that the event has no damage on the front tie rod. This is most likely because a short impulsive impact (such as a stone hitting the accelerometer on the rear wheel) is unlikely to affect the front tie rod. Further studies into anomaly detection and correction are recommended to address these possible problems.

EXPERIMENT 9

Experiment 9 – Using Lalanne Damage Spectrum instead of Rupp

This experiment is used to compare performance when using a Lalanne-based damage spectrum instead of a Rupp-based spectrum. The Lalanne spectrum uses a different frequency filter than Rupp. Lalanne is based on a single degree of freedom (SDOF) response filter, whereas Rupp is based on a band-pass filter. The Rupp filter covers a large range of frequencies whereas Lalanne is quite finely tuned to a specific tonal frequency.

The Lalanne filter offers a fine degree of frequency precision. In this example the dynamic amplification factor was reduced to Q=5 to reduce that precision. In theory, the increased precision would require many more filter steps (e.g. 32 for the frequency range 0-32Hz); however, only 5 frequency intervals were used in this experiment so that the results could be compared directly with the equivalent Rupp method.

Exp. 9 Objective

This experiment tries to repeat experiment 6 using the Lalanne, rather than the Rupp, Damage Spectrum. The objective is to demonstrate the accuracy of predicted damage values vs. calculated damage values over a range of randomly selected samples of data. Comparisons are made under both curb and gross weight conditions as used in the transfer function derivation.

Exp. 9 Method

The transfer function is calculated using a range of proving ground surfaces and ground speeds as described in experiment 6. The transfer function is derived under both curb and gross weight conditions for dataset 1151 measurements. The damage is validated using several random proving ground samples which are concatenated to create a single long event.

- Test #1 considers the same proving ground spectrum as used to derive the transfer function – this represents the ‘best-case’ scenario.
- Test #2 considers the entire set of curb weight samples from dataset 1151.
- Test #3 considers the entire set of gross weight samples from dataset 1151.
- Test #4 considers the entire set of curb weight samples from dataset 1152.
- Test #5 considers the entire set of gross weight samples from dataset 1152.

Exp. 9 Conclusion

Results show good to tolerable correlation with the measured damage. Maximum error is within a factor of 4. The equivalent Rupp approach demonstrated excellent correlation with the measured damage and was found to out-perform Lalanne in this case (maximum error in experiment 6 was 1.2.) Lalanne would respond better to narrow-band excitation and resonant response characteristics at higher frequencies; however, it still offers satisfactory performance under low frequency ground-induced vibration of quasi-static structures.

The available data sets did not contain measured strains for body mounted components, which is why this analysis focused on structural components.

Table 1: Summary of Results

	Transfer Function Definition				Verification Events				Damage
Exp.	Vehicle	Weight	Events	Test	Vehicle	Weight	Events[1]	Speed	Ratio
Exp 1	1151	Curb	Random	Test 1	1151	Curb	Transfer Function	Mix	0.859
				Test 2	1151	Curb	Random	Mix	0.802
				Test 3	1151	Curb	Random	Mix	0.737
				Test 4	1151	Curb	All	Mix	1.048
	Accel Profile: LF Wheel			Test 5	1152	Curb	Random	Mix	1.153
	Component: LF Tie Rod			Test 6	1152	Curb	All	Mix	1.048

Table 1: Summary of Results (cont.)

	Transfer Function Definition				Verification Events				Damage Ratio
Exp.	Vehicle	Weight	Events	Test	Vehicle	Weight	Events[1]	Speed	
Exp 2	1151	Curb	Random	Test 1	1151	GVW	Transfer Function	Mix	1.256
				Test 2	1151	GVW	Random	Mix	1.914
				Test 3	1151	GVW	All	Mix	1.441
	Accel Profile: LF Wheel			Test 4	1152	GVW	Random	Mix	0.575
	Component: LF Tie Rod			Test 5	1152	GVW	All	Mix	0.642
Exp 3	1151	Curb	Random	Test 1	1151	Mix	Random	Mix	1.260
				Test 2	1151	Mix	All	Mix	1.500
	Accel Profile: LF Wheel			Test 3	1152	Mix	Random	Mix	1.015
	Component: LF Tie Rod			Test 4	1152	Mix	All	Mix	0.809
Exp 4	1151	Curb	Random	Test 1	1151	Mix	Be, Bu, Ch, Gr	<30mph	1.300
				Test 2	1152	Mix	Be, Bu, Ch, Gr	<30mph	0.787
	Accel Profile: LF Wheel			Test 3	1151	Mix	Pa, Ro	>30mph	1.763
	Component: LF Tie Rod			Test 4	1152	Mix	Pa, Ro	>30mph	0.720
Exp 5	1151	Curb	Random	Test 1	1151	Mix	Pe, Ro	Mix	1.646
				Test 2	1152	Mix	Pe, Ro	Mix	0.852
	Accel Profile: LF Wheel			Test 3	1151	Mix	Be, Bu	Mix	1.300
	Component: LF Tie Rod			Test 4	1152	Mix	Be, Bu	Mix	0.889
Exp 6	1151	Mix	Random	Test 1	1151	Mix	Transfer Function	Mix	0.914
				Test 2	1151	Curb	All	Mix	1.045
				Test 3	1151	GVW	All	Mix	1.002
	Accel Profile: LF Wheel			Test 4	1152	Curb	All	Mix	1.002
	Component: LF Tie Rod			Test 5	1152	GVW	All	Mix	0.885
Exp 7	1151	Mix	Be, Bu	Test 1	1151	Curb	Be, Bu, Ch, Gr	Mix	0.963
			<30mph	Test 2	1151	Curb	Pa, Ro	>30mph	0.238
	Accel Profile: LF Wheel			Test 3	1152	Curb	Be, Bu, Ch, Gr	Mix	1.151
	Component: LF Tie Rod			Test 4	1152	Curb	Pa, Ro	>30mph	0.379
Exp 8	1151	Mix	Random	Test 1	1151	Mix	Transfer Function	Mix	1.419
				Test 2	1151	Curb	All	Mix	2.174
				Test 3	1151	GVW	All	Mix	1.908
	Accel Profile: LR Wheel			Test 4	1152	Curb	Random	Mix	1.919
	Component: LF Tie Rod			Test 5	1152	Curb	All	Mix	0.830
Exp 9	1151	Mix	Random	Test 1	1151	Mix	Transfer Function	Mix	2.080
Lalanne				Test 2	1151	Curb	All	Mix	2.473
				Test 3	1151	GVW	All	Mix	3.035
	Accel Profile: LF Wheel			Test 4	1152	Curb	All	Mix	3.971
	Component: LF Tie Rod			Test 5	1152	GVW	All	Mix	2.992

1 - Event Descriptions: Be - Belgium blocks, Bu - Bumps, Ch - Churchville,
Gr - Gravel, Pa - Paved, Pe - Perryman, Ro - Rounds

DISCUSSION

Loading (and hence damage) on structural components is roughly proportional to the vehicle weight, acceleration and frequency. This study has considered vehicle weight in terms of curb weight and gross vehicle weight. Experiments show that damage does not scale linearly with weight. Therefore, if the transfer function is derived under one loading condition, the results do not correlate as well with service in another loading condition. However, the nonlinear effect is not excessive and any error appears to be within acceptable tolerances for fatigue damage analysis. Further experimentation shows significant improvement in prediction by considering a range of weight conditions when deriving the transfer function.

Acceleration contributes to damage on the basis that damage is proportional to strain which is proportional to displacement, and displacement is obtained by double integrating the acceleration signal. General acceleration levels are measured on the vehicle to determine the severity of the terrain-induced loads on structural components such as chassis, steering and suspension components. Terrain-induced acceleration load levels vary with vehicle weight and speed. Acceleration is accounted for explicitly in this method.

Frequency also contributes to damage in that damage is proportional to the number of fatigue cycles, with higher frequencies yielding more cycles. However, fatigue failure is driven by the release of strain energy and since strain is proportional to force / frequency^2, higher frequencies have a lower contribution to damage. Resonant response at particular frequencies (such as wheel hop frequencies) can contribute significant additional damage at these particular discrete frequencies. Frequency is accounted for explicitly in this method by filtering the acceleration response into discrete frequency bands.

CONCLUSION

This paper summarizes the Rupp Durability Transfer Concept and compares it against the Lalanne approach. A number of experiments are presented that demonstrate the possibility for good correlation between measured acceleration on a vehicle and damage at a remote location. Correlation diminishes as coherence diminishes. Therefore, it is important to select representative locations for the accelerometers relative to the critical components. For best results, the transfer function requires a good range of usage conditions – i.e. representative terrain roughness, speed profile and vehicle weight conditions. The Rupp Durability Transfer Concept offers a good solution for low frequency terrain-induced fatigue whereas Lalanne offers a better solution for higher frequency resonance-induced failures.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Army TACOM Life Cycle Command under Contract No. W56HZV-08-C-0236, through a subcontract with Mississippi State University, and was performed for the Simulation Based Reliability and Safety (SimBRS) research program.

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Army TACOM Life Cycle Command.

REFERENCES

[1] Rupp, A.; Masieri, A.; Dornbusch, T. "Durability Transfer Concept for the Monitoring of the Load and Stress on Vehicles." Innovative Automotive Technology Conf., Bled, Slovenia. 21-22 April 2005.

[2] Halfpenny, A.; Walton, T.C. "CBM for Vibrating Equipment on Rotorcraft." American Helicopter Society Technical Specialists' Meeting on Condition Based Maintenance. Huntsville, AL, USA. 10-11 February 2009.

[3] Halfpenny, A. "A New Terrain Sensing System based on Fatigue Damage Spectra." IVSS. 2006.

[4] Lalanne, C. Mechanical Vibration & Shock, Volumes II & V. Hermes Penton Ltd. London. 2002.