 SDHM, vol.6, no.2, pp.69-76, 2010

Advancements in the Automotive Durability Process

Mark Pompetzki[1], Brian Dabell[1] and Xiaobin Lin[2]

Structural integrity in terms of automotive durability is a detailed process that incorporates many technical areas. The current durability process for automotive applications involves understanding operational load inputs, the stresses and strains caused and the response of the material, performing fatigue tests, calculating fatigue life and interpreting results. There are many variations on this process depending on the application, materials, available information, methods, etc. This paper presents a general approach for the durability process in automotive applications and highlights a number of new advancements. These advancements include understanding the service operating load conditions through improved usage based monitoring, characterizing new materials together with their associated damage models, enhancing and automating data manipulation through straightforward, consistent and rapid process based analysis, creating test profiles for random loading and accelerating CAE based durability analysis. The impact and importance of the advancements is illustrated by reference to each part of the durability process as well as the process itself.

1 Durability Process

Fatigue life can be determined using field testing, laboratory testing and/or analytical methods as shown by the general durability process in Figure 1. Traditional methods for fatigue life assessment are based on field testing and/or laboratory testing, while analytical approaches have become increasingly integrated in the overall approach over the last decade. To understand and evaluate durability performance early in product design a clear and straightforward durability process is required, which includes realistic inputs in terms of operating environment and material characterization, fast analytical methods and rapid testing techniques, while maintaining good correlation between test and analysis to provide confidence in results.

[1] HBM-nCode Products, 26555 Evergreen Road, Suite 700, Southfield, MI 48076, USA
[2] HBM-nCode Products, Unit 401, Building 9, No. 99 TianZhou Road, Shanghai 200233, P. R. China

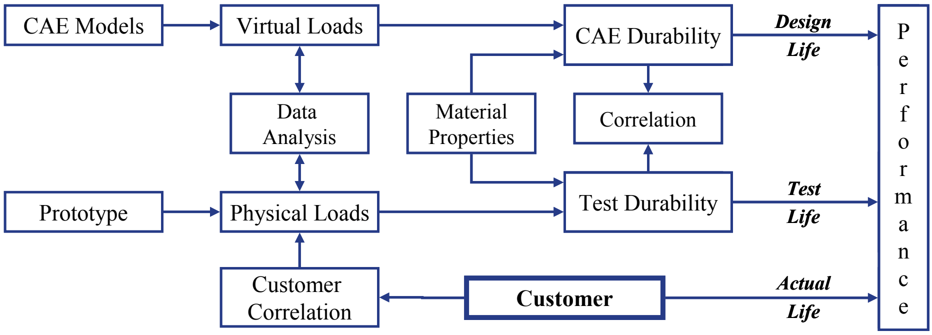

Figure 1: The General Durability Process

The fatigue life of a component is governed by the loading environment to which it is subjected, the distribution of stresses and strains arising from that environment, and the response of the material from which it is manufactured (Plaskitt and Musiol [2002]). These are the main inputs to any fatigue analysis (component geometry, service loading and cyclic material properties) and can be derived by physical or analytical methods or a combination of both. Service loading can be measured in the field, measured on proving grounds, estimated virtually using multi body dynamics (MBD) or estimated using a combination of these methods, such as measured wheel loads as input into an MBD model to derive sub-system or component loading.

All loads measured in the field or derived analytically need to be processed to identify and eliminate anomalies and characterize the data into useful information that can be used by engineers. Another key to accurate fatigue predictions is characterizing material behavior for cyclic loading, especially given the range of new materials that are is use today. Finite element (FE) analysis results define the local stress-state for a component given specific loading conditions. These are then combined with the loading environment and material behavior to predict the local stress and/or strain history that is fed into the fatigue prediction algorithm to estimate life. Correlation between analytical and test results is a critical step in this process to ensure that the analytical inputs and results are valid, thus developing confidence in these methods. The remaining sections provide details into advancements in a number of these areas.

2 Advancements: Physical Measurements - Hums

Historically, physical measurements have involved recording data for design, testing and, to a limited extent, actual customer usage. As a result of increased computer power and storage capacity, software advancements and new prognostics methods, it is now possible to monitor significant information about the current performance of vehicle fleets and predict future performance. This capability is called HUMS (Health and Use Monitoring Systems) and represents the integration of the durability process, described earlier, for on-board monitoring of vehicle durability and performance – measure, process, predict. This prognostic approach is concerned with predicting the residual life of components. It uses a quantitative record of the operational loads experienced by the vehicle and processes this through an analytical model to determine the progressive cumulative damage on systems/components as shown in Figure 2.

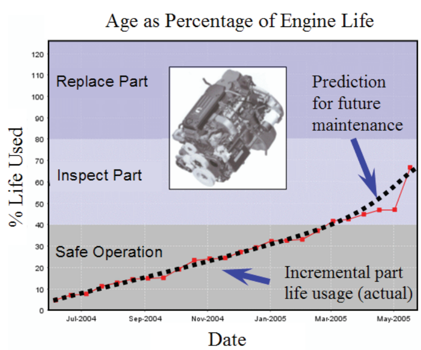

Figure 2: Vehicle Prognostics

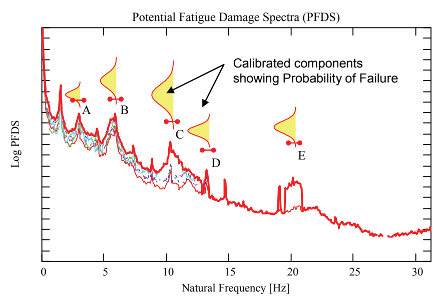

Figure 3: Potential Fatigue Damage Spectrum

The analytical model used is dependent on the component being examined. For example, components mounted on the vehicle body (e.g. electronics, radiator, etc.) have failure locations usually dominated by a single natural frequency; this is known as a “Single Degree of Freedom (SDOF)” system. The structural model involves filtering the input acceleration signal to assess the damage for each frequency. Figure 3 shows potential fatigue damage versus frequency and also shows how each successive mission has contributed to the total damage to date. Another example is driveline components, where the key inputs are proportional to the torque of the engine that can be obtained directly from the vehicle bus (an internal communications network that interconnects components within a vehicle) and combined with engine speed data to identify the number of cycles experienced in service. Monitoring of the axle speed provides information to determine the gear engaged and allows calculation of the accumulated damage separately for different components within the driveline.

3 Advancements: Data Processing – Process Based Analysis

Effective engineering design and development depends critically on a good understanding of operational loads experienced by systems/components. The process of engineering design and development generates very large volumes of data – measured and derived. Searching for data, re-formatting and preparing data for analysis consume approximately 70% of engineers' time nowadays. Another challenge is using consistent processes to analyze the data throughout organizations and capture legacy information and methods for processing data rather than re-inventing the process every time analysis is undertaken.

The value and availability of data is enhanced dramatically by creating consistent automated processes to handle and access measured and derived data where all relevant pedigree information is also associated with the data. The key is converting measured data into useful information on which the engineer can base decisions. As we see the emergence of "six sigma" processes, linking data with its pedigree and creating consistent processes increases in importance. It has been shown that creating such processes has dramatically accelerated the conversion of measured data (e.g. from the proving ground) into useful information for engineers to use in the product design, development and evaluation process. An example process is shown in figure 4.

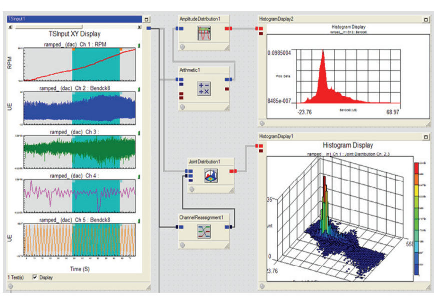

Figure 4: Process Based Analysis

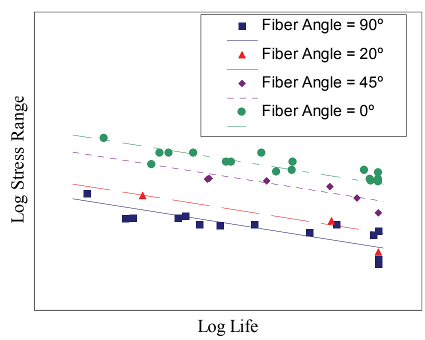

Figure 5: Fatigue Strength with Fiber Alignment

4 Advancements: Materials – Short Fiber Composites

Recently, the automotive industry has seen a shift to lighter materials, including the use of short-fiber composites as structural components. The key aspects to incorporating any new material in the durability process is to understand and characterize the material behavior, adjust the durability process and enhance the fatigue calculation to incorporate new failure modes as described by Vervoort [2005]. If one attempts to analyze a component made from a new material with existing methods, the results are often inaccurate. For short-fiber composites, the fatigue life curves vary with fiber alignment (Figure 5), which must be taken into account in the durability process and the fatigue calculation. Fiber angle is calculated using flow simulation to represent the manufacturing process and is transferred into the FE analysis to calculate the local stress state for each element of the model. The fiber angle and local stress state are then brought into the fatigue calculation and combined with the service loading condition and the material properties to predict life. A critical plane approach is used to predict performance and take into account fiber orientation and associated directional properties for each element of the model. By understanding the failure modes and the key parameters to characterize a material the durability process and fatigue algorithms can be modified to incorporate new material characteristics.

5 Advancements: Test Durability – Accelerated Testing

Numerous methods exist for accelerating tests for both deterministic and stochastic events as described by Halfpenny [2007]. Testing for deterministic events are represented in the time or cycle domain and accelerated methods include load amplitude modification, small cycle editing, block cycle, and time correlated damage to name few. Testing for stochastic events are represented in the frequency domain and incorporate vibration testing on electro-dynamic shakers or MAST tables (Multi-Axis Shake Tables). Accelerated testing methods for vibration testing include a recent development called mission profiling and test synthesis based on the fatigue damage spectrum (Halfpenny and Kihm [2006]). This technique is used to derive a rig test that contains at least the same damage potential as the real environment for which the component is intended to survive by combining the fatigue damage spectra for random and extreme events. The fatigue damage spectrum (FDS) is the damage potential of a vibration input for a component over a range of natural frequencies and can be calculated for time histories or PSDs and summed over all events to represent the service environment as shown in Figure 6. In order to create a test PSD, the shock response spectrum (SRS) and the extreme response spectrum (ERS) must also be calculated. The SRS represents the most likely extreme amplitude response of a SDOF system to an input time signal, while the ERS is the equivalent for a PSD excitation. An accelerated test is obtained by synthesizing a test PSD with the same damage potential as the FDS, while bounding the solution with the envelope of the ERS and SRS. In this manner an accelerated PSD can be derived that minimizes test time, while ensuring lifetime maxima are covered by the test and the risk of failure due to a severe loading is minimized.

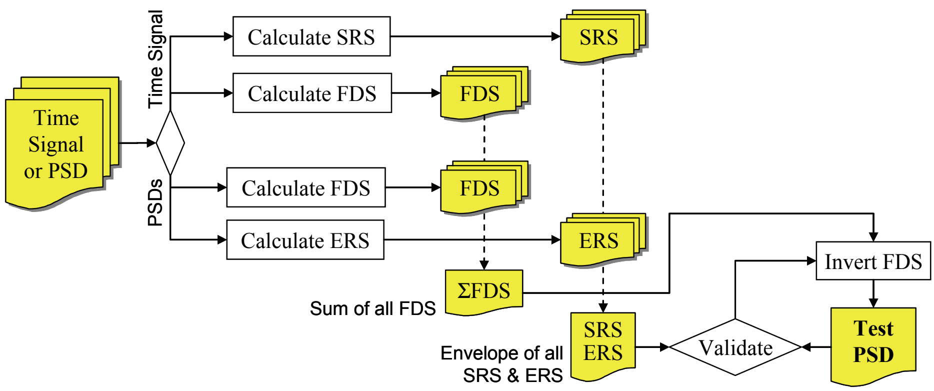

Figure 6: Mission Profile and Test Synthesis

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Non-Proportionality Factor (NP)</td></tr>
<tr><td>$0 \le NP \le np_1$</td><td>$np_1 \le NP < np_2$</td><td>$np_2 \le NP$</td></tr>
<tr><td rowspan="4">Biaxiality Ratio (a)</td><td>$-1 \le a < a_1$</td><td colspan="2">Critical plane – dominant and 90 degree planes
No Mean stress correction</td><td>Multiaxial method
No mean stress correction</td></tr>
<tr><td>$a_1 \le a < a_2$</td><td>Uniaxial Calculation
Mean stress correction</td><td>Critical plane, Dominant dir.
Mean stress correction</td><td>Multiaxial method
Mean stress correction</td></tr>
<tr><td>$a_2 \le a < a_3$</td><td>Signed Tresca
Mean stress correction</td><td>Type B crack, Dominant dir.
Mean stress correction</td><td rowspan="2">Multiaxial method
Type B crack
Mean stress correction</td></tr>
<tr><td>$a_3 \le a \le 1$</td><td colspan="2">Type B crack, Mean stress correction</td></tr>
</table>

a_1, a_2, & a_3 and np_1 & np_2 are configurable thresholds

Figure 7: Example Configuration for Adaptive Strain-Life Prediction

6 Advancements: CAE Durability – Adaptive Fatigue, Hotspot Detection

Analytical techniques for durability use the results of the CAE model to predict the fatigue life at each element within the structure. As FE models become larger and more complex, it is important to minimize the time spent in predicting and post processing durability results. There are numerous techniques available including adaptive fatigue and hotspot detection.

A complex multi-axial algorithm requires significantly more computational effort than a simple uniaxial method and hence it would be inefficient to use such a complex method for all elements in the structure. Adaptive fatigue is a technique used to select the best and most efficient prediction technique based on the biaxiality ratio and the degree of non-proportionality. These two parameters are calculated from the local stress or strain state over time (HBM-nCode Products [2009]) and used to select the fatigue algorithm for each element. An example configuration is shown in Figure 7 for adaptive strain life prediction.

Post-processing fatigue results is a very important part of the durability process and numerous techniques are available to quickly focus on the areas of interest. This can be done in tabular form using pre-sorted tables based on damage magnitude, components in the structure, events that are critical, etc. It may also be done graphically with hot-spot detection, where the critical location in each area is highlighted. Primarily the analyst is interested in understanding the element with the highest damage in a local region (i.e. the local maximum) and not just a list of damaged elements from highest to lowest. Using hot spot detection these critical locations can be quickly highlighted and further analysis can be focused in those areas. Although fatigue analysis generally focuses on the critical locations, much can be learned from areas that are not critical, as these are potential locations for cost savings.

7 Summary

This paper describes the current durability process and recent advancements in usage based monitoring, rapid process based analysis, characterization and analysis of new materials, accelerated testing methods and accelerating CAE based durability analysis. Applying these powerful methods provides the means to accelerate new product development, better understand the opportunities offered by new materials, optimize designs, and improve laboratory and proving ground test procedures. The emergence of prognostic methods that predict structural performance in-situ on vehicles and other high value assets provides the means to better manage maintenance and replacement strategies with associated reduced cost of ownership. The key to success is a comprehensive understanding of the key factors influencing durability – operating loads, materials properties, design geometry and manufacturing processes.

References

Halfpenny, A. (2007): Accelerated Loading for Fatigue Analysis and Rig Testing, *Fatigue*, 6^{th} Engineering Integrity Society International Conference on Durability and Fatigue, Cambridge, UK.

Halfpenny, A., Kihm, F. (2006): Mission Profiling and Test Synthesis based on Fatigue Damage Spectrum, Ref. FT342, 9^{th} *Intl. Fatigue Congress*, Atlanta, USA.

HBM-nCode Products (2009): DesignLife Theory Guide, Version 5.1, Sheffield, UK.

Plaskitt, R., Musiol, C. (2002): Developing a Durable Product, *ASAE Distinguished Lecture #26, Agricultural Equipment Technology Conference*, Kansas City, MS, ASABE, St. Joseph, MI.

Vervoort, S. (2005): Fatigue of Engineering Polymers, *MSC.Software 2005 Virtual Product Development Conference*, Munich, Germany.