

Durability Test Time Reduction Methods

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ABSTRACT

Laboratory based durability simulation has become an increasingly important component of vehicle system design validation and production release. It offers several advantages over field testing which has driven its adoption in the automotive and military sectors. Among these advantages are 1) repeatability, 2) earlier testing, 3) isolation of subsystems or components and 4) ability to compress and/or accelerate the testing. In this paper we present time-domain methods and techniques adapted, implemented and used at TARDEC to reduce the time required to perform a laboratory durability test of a full vehicle system, subsystem or component. Specifically, these methods approach a durability schedule holistically by considering all events/surfaces, repeats and channels of interest. They employ the standard Generic Stress Life (GSL) approach, utilizing rain flow cycle counting and a minimum-average method of identifying segments of the events which are less severe. The mathematical methods are presented as well as a case study in which the methods are used. The case study illustrates the effectiveness of the compression methods at five different levels of retained severity. Finally, we discuss joining methods and demonstrate that the joining method chosen has an effect on the overall test compression performance and has the potential to either degrade retained severity or lengthen the test.

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INTRODUCTION

Background and Motivation

As the Army develops and upgrades its ground vehicle fleet, reliability is a key driver for design and manufacturing processes. Traditionally, reliability metrics are quantified as requirements which the vehicle developer is expected to meet. The Army's Test & Evaluation (T&E) community then tests a set of these vehicles to confirm that these reliability metrics are met [4]. If they are not met, the T&E product team, Program Manager (PM) and contractor then enter into a process of test-fix-test commonly referred to as reliability growth [1]. Standard processes in the Army fall into two categories, Developmental Test (DT) and Operational Test (OT) [4]. This paper primarily addresses DT which is focused on confirming that technical requirements are met. For reliability, a durability schedule is normally derived from the Operational Mode Summary/Mission Profile (OMS/MP) which specifies the mixture of terrains on which the vehicle is expected to operate. An example of such a specification would be 40% primary roads, 30% secondary roads, 30% trails & cross-country. Additionally, an annual usage in terms of mileage is provided which is then extrapolated to a lifetime estimate that varies from 6,000 miles to 20,000 miles depending on the vehicle. These specifications are normally decomposed by the test community by mapping these terrain types to particular courses at a proving ground at particular speeds (note that one terrain type may be further represented by multiple proving ground courses).

Both the Tank Automotive Research Development and Engineering Center (TARDEC) and Aberdeen Test Center (ATC) have been investing in laboratory facilities to perform durability and reliability testing in a laboratory environment [6, 7, 8, 28, 29]. A couple of these facilities are shown in [Figures 1 & 2](#).

Such testing devices are common in the automotive industry [9,10,12,14,16,18,22,26] and they are used to great effect to assist in the design validation of new vehicle models. Advantages of laboratory testing are as follows:

- Ability to test earlier at a subsystem level
- Ability to precisely control test inputs
- Ability to instrument, monitor and inspect
- Ability to compress and/or accelerate the testing
- Repeatability of test for design iterations

Disadvantages of laboratory testing are as follows:

- It does not test the full system, only specific subsystems
- It does not expose the systems to all environmental effects such as dust, mud, rain, sun, temperature, etc.



Figure 1. N-Post Simulator at TARDEC.



Figure 2. Spindle Coupled Vehicle Durability Simulator (VDS) at ATC.

As listed among the advantages of laboratory testing are the ability to accelerate and/or compress the test. As laboratory-based durability testing becomes more commonplace in the Army T&E process, TARDEC is adapting and customizing industry methods, techniques and tools to compress test duration to make lab testing as attractive as possible. This paper presents methods recently adapted and implemented at TARDEC to compress a test across an entire durability test schedule.

Test Compression Background

As stated in the title of this paper, test compression is about test time reduction. For our purposes we will use the following definition:

Test Compression: A process by which a durability test schedule is shortened in duration to the maximum extent possible by removal of time segments while maintaining a desired portion of the original severity for the overall test.

Note that “severity” needs to be distinguished from actual fatigue damage. Often data acquired for test development do not include strain channels for actual fatigue computation. By “severity” we mean the use of other types of channels (i.e. acceleration, load, displacement, etc.) as generic signals which are analyzed using stress life methods. This is normally referred to as Generic Stress Life (GSL). Also, note that compression as defined here shortens test time only by removing portions of the schedule [6,13,23] as opposed to acceleration [5,15,17,20] which seeks to further shorten test time by disproportionately adding more severe events, amplifying the amplitudes, or shifting the frequency. For tests

which are inertially reacted one must be careful about the manipulation of simulator inputs so that they do not excite unnatural dynamics and so that actual dynamics are excited as they would be in the field. It is for this reason that we are considering segment-based compression methods here as opposed to peak-valley, frequency-domain or block cycle methods.

Methods of compression range in complexity. The simplest method of compression is to not test on surfaces which simply do not challenge durability of the test area under focus (e.g. removing paved surface miles from a suspension test). The next approach is to perform editing on an event or file basis. Methods commonly used in industry address compression at the file or event level [6]. One standard approach divides a time history into fixed size segments (i.e. 1 to 5 second chunks) and then performs statistics on each segment which could be RMS, max, min or range. (This method is used in industry software packages such as Remote Parameter Control[®] (RPC) among others. There it is often referred to as time-history editing.) This process is performed for each channel in a file. The “low” regions for the channels are then aggregated using logical operations such as unions or intersections. These aggregate regions are then deleted and retained severity is assessed using fatigue estimation which is typically performed using rainflow cycle counting and stress-life, strain-life or pseudo-damage techniques. Approaches which employ these or similar techniques may be found in the literature [13].

The approach presented in this paper takes a few additional steps to look at time editing from a holistic point of view, namely, it evaluates candidate segments based on a severity score and it also evaluates them with respect to the composition of all the events in a test. The paper briefly reviews the durability simulation process, presents the test compression approach, presents a case study and then concludes.

DURABILITY SIMULATION PROCESS

To develop a durability test in the laboratory, a number of steps need to be completed. A rough process for performing a full-vehicle durability test is as follows:

1. Acquire course data in a Road Load Data Acquisition (RLDA)
2. Import, convert and analyze the data.
3. Select surfaces to represent full test schedule & compute repeats for each surface to add up to the required distance.
4. Edit/compress the surfaces to minimize time and retain a pre-determined amount of damage.
5. Execute drive file development (DFD) for each surface and recompute severity retention.
6. Perform additional DFD or modify repeats to achieve a satisfactory road to lab correlation.
7. Run the test and monitor the results.

The focus of this paper is on step 4.

The RLDA normally acquires the following minimum suite of instrumentation:



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- Vertical acceleration for each spindle
- Suspension displacement for each wheel
- Vehicle speed
- Accelerometers mounted on the chassis
- Strain gages mounted on components of interest

During the RLDA, each course or surface is recorded for multiple passes, sometimes at multiple speeds. The events which are chosen to represent the durability schedule are selected to be typical of the passes over a given terrain. If these events are lengthy, the test engineer may extract a shorter portion to represent the whole course. (Experience and engineering judgement is required.) These representative events comprise the full set of events from which to extract desired responses for drive file development. Implied in this process is the ergodicity of the recorded laps (i.e. all laps on the proving ground course are represented by the data collected in the RLDA). This method of recording field responses has the advantage that it captures the response of the vehicle to the excitation of the terrain, so it automatically encapsulates all of the dynamics of the vehicle system such as resonances.

After the completion of this process, a baseline durability schedule is established consisting of a set of a set of N_e events represented as time history files. Each of these events has N_c channels for which test compression will be employed (i.e. the event may contain more channels). Each varies in length and we denote the length of each event as L_j , where $j = 1, \dots, N_e$ and each event is repeated R_j times in the durability schedule.

TEST COMPRESSION APPROACH

This section begins with a discussion of the rainflow cycle counting method and then presents the test compression algorithm.

Rainflow Counting Method

Counting methods were initially developed for the study of fatigue damage generated in aeronautical structures. The signal to be subjected to analysis is a random stress $\sigma(t)$. For narrow-band processes, the peaks often occur between zero crossings, thus establishing a strong connection between the number of peaks and the range and number of reversals. In this case, the counting of peaks makes it possible to compute a histogram which can then be transformed into a stress spectrum (which correlates fairly well with laboratory fatigue experiments). On the contrary, for broadband signals, several peaks often appear between zero crossings, which makes it difficult to determine the number and range of cycles absorbed by the structure. In the search for ways to correlate broad-band stress time histories with fatigue, many alternatives were considered and the rainflow cycle counting method was found to correlate well with experimental data. The rainflow counting method was initially proposed by M. Matsuiski and T. Endo [19,11] to count the cycles or the half-cycles of strain-time signals. Counting is carried out on the basis of the stress-strain behavior of the material considered [24]. The extracted cycles are in conformity with those of the tests of constant amplitude from which the predictions of fatigue life are generally carried out.

Let us imagine (Figure 3), to describe this method and to explain the origin of its name, that the time axis is vertical and that the signal $\sigma(t)$ represents a series of roofs on which water falls. Water drops are sequentially released at each extrema and based on which flows are interrupted by flows from above, a set of full and half cycles can be extracted from the time series.

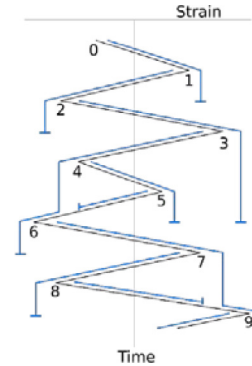


Figure 3. Rainflow: The drop is released from the largest peak. [27]

A full description of the algorithm can be found in ASTM E1049-85 [3].

The output of the rainflow method consist of a set of stress ranges along with a number of repetitions which may then be used to compute damage. In the work presented here, we employ an exponential Generic Stress (or Amplitude) Life (GSL) damage law expressed as

$$\sigma = \sigma_0 (N_f)^b \quad (1)$$

where N_f is the number of cycles to failure at signal range σ , σ_0 is the failure strength for 1 cycle (often referred to as the Y-intercept), and b is the slope, which is assumed as -0.2 for steel. We can solve this equation for N_f to obtain

$$N_f = \left(\frac{\sigma}{\sigma_0} \right)^{\frac{1}{b}} \quad (2)$$

which gives the number of cycles to failure for a given cycle of range σ . From the rainflow counting, we may extract our set of ranges as $\{\sigma_1, \sigma_2, \sigma_3, \dots, \sigma_m\}$ for m cycles. We may then estimate severity (or pseudo-damage) by computing the N_{fi} from σ_i using (2) and then associate partial severity with $\frac{1}{N_{fi}}$ which may be linearly accumulated using Miner's rule as

$$D = \sum_{i=1}^m \frac{1}{N_{fi}} \quad (3)$$

where we typically ignore ranges which are less than some threshold σ_r . Typically we choose the minimum threshold to be associated with 10^9 cycles. Our implementation of the rainflow-severity estimation