

Durability and Reliability Test Planning and Test Data Analysis

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ABSTRACT

Durability/reliability design of products, such as auto exhaust systems, is essentially based on the observation of test data and the accurate interpretation of these data. Therefore, test planning and related data analysis are critical to successful engineering designs. To facilitate engineering applications, testing and data analysis methods have been standardized over the last decades by several standard bodies such as the American Society for Testing and Materials (ASTM). However, over the last few years, several effective testing and data analysis methods have been developed, and the existing standard procedures need to be updated to incorporate the new observations, knowledge, and consensus.

In this paper, the common practices and the standard test planning and data analysis procedures are reviewed first. Subsequently, the recent development in accelerated testing, equilibrium based data fitting, design curve construction, and Bayesian statistical data analysis is presented. The challenge posed by small sample size is emphasized and the effectiveness of the newly developed methods is demonstrated with several worked examples.

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INTRODUCTION

Product designers and manufacturers are under continuous and increasing pressure to reduce the "time-to-market" of new products while assuring high levels of durability and reliability of these products [1, 2]. However, the durability life and warranty time of vehicle components and systems are usually required to last relatively long time, e.g. 10-15 years, which is unbearable for laboratory testing under normal operating conditions. Therefore, the time and efforts involved in testing, especially in early development stage, can be very expensive. To reduce the time-to-market and the cost in product design and validation, accelerated testing is often adopted [3]. Accelerated tests are conducted at stress levels higher than that experienced in service condition, and the life of the components and systems under service loading conditions can be estimated using appropriate extrapolation approaches.

Furthermore, durability and reliability performance of products is one of the most important concerns for almost all vehicle systems [1], and the performance and durability life analysis is essentially based on test data and the accurate interpretation of the data. However, test data such as fatigue test data always contain an inherent scatter that cannot be substantially reduced even under controlled testing

conditions. Eventually, repeats of tests under the same testing condition are often required to capture the uncertainty, scatter characteristics, and failure probability of the test data. Additionally, tests with several stress levels are usually conducted to cover a wide range of stress levels, which further lead to more test samples. Therefore, testing plan, sample size and allocation, testing sequence must be carefully determined in order to find a reasonable compromise between the test accuracy and the cost of the tests. Moreover, to ensure the accuracy in life assessment, sophisticated/efficient statistical analysis methods have to be used to obtain the statistical information, such as mean and scatter of the test data, and to construct design curves for engineering applications [1]. Mathematical analysis of durability data is further complicated by many factors such as heteroscedasticity (unequal variance and a "funnel shape" visually in a plot), unknown distribution, censored data, multiple failure modes, nonlinearity etc. [3].

In this paper the existing engineering test planning and data analysis procedures are reviewed first. Subsequently, several new concepts, approaches, and procedures developed recently, mainly contributed by the authors of this paper, are introduced with foci on four related aspects, which are essentially the backbones of all durability and reliability analysis and design methods: accelerated testing, equilibrium

based data analysis, design curve construction, and Bayesian statistics for sample size reduction. Several recently reported methods dispersed in the literature are now synergistically incorporated into a single paper to serve as a guide for design and product validation engineers in their test planning and data analysis.

ACCELERATED TESTING PLAN

Test planning and plan execution are crucial to successful product development. Test planning involves scheduling and estimating test process, establishing standard procedure and providing test details such as sample size, sample allocation and testing sequence [4, 5]. The goal of test planning is to give an overall picture for testers to follow before testing. Testing planning is especially important for tests involved in expensive and time consuming testing procedures. Major considerations in a test plan are: cost, timing, accuracy, application target, capability. A test plan is a dynamic document and needs to be updated depending on the specific situation involved in product development. Test planning and data analysis are mutually affected and one should be considered when the other is scheduled. Depending on the scope of the test, a test plan can be divided into several phases and levels of testing.

Several test plans, such as the traditional plan, the optimum plan, and the compromised plan, for accelerated testing have been well developed for accelerated testing [3]. The traditional test plan, which has equally spaced test stress levels and equal numbers of specimens at each level, has been adopted by many engineering standards such as the ASTM for conventional service testing as well as for accelerated testing [3, 4, 5]. However, traditional plans generally require 25 to 50 % more specimens for the same accuracy as good plans [3]. The optimum test plan is obtained by minimizing the variance of the predicted mean values of the dependent variable and it yields the most accurate estimates of life at the design stress [3]. Yang presented the best compromise three-level [6] and four-level [7] constant stress accelerated life test plans for Weibull distributions with different censoring times. The general conclusion of the optimum test plan is that more test samples should be placed on the lower stress level. Two extremes are very informative [3]: (1) if the lowest test stress equals the design stress, all specimens should be run at the lowest test stress; (2) if the service stress is much below the lower stress, the specimens should be equally located at the lower and higher stress levels, which is the case for the traditional test plan. However, the confidence interval at a certain reliability level obtained using all of the existing methods for, say, fatigue S-N data, is generally in concave shape, which is more severe for test data with small sample size, and thus inconvenient and inaccurate for accelerated testing.

Design curve based on certain reliability and confidence at a given stress level is an important concept in engineering designs, and the associated accelerated testing procedures for

design curve must be developed. Two-stress level and equal-partition principle based multiple-stress level accelerated testing procedures have been developed for data with homoscedastic characteristics [8, 9]. For test plan with two stress levels, the equal partition principle based method can be approximately reduced to the two-stress level method for homoscedastic data [9]. Both the two-stress level method and the equal partition method lead to design curves paralleling to the mean curve, therefore, suitable for accelerated testing. However, there are some differences between these two methods: the two-stress level method can be applied only to testing with two stress levels and it is more conservative [9].

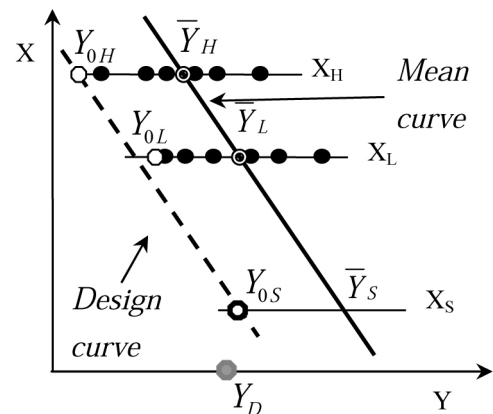


Figure 1. Accelerated testing procedure for linear data with homoscedastic characteristics

Based on the tolerance limit concept [8, 9], the following two-stress level accelerated testing procedure has been proposed for linear homoscedastic data with arbitrary data points at each stress level [10], Fig.1.

The procedure:

1. Conduct accelerated test by following the traditional test plans [4, 5];
2. Obtain the mean curve $\bar{Y}$ from test data with the least squares method;
3. Calculate the standard deviation s_H and s_L . The subscripts H and L represent higher and lower stress levels, respectively;
4. Calculate the low bound Y_0 with a certain criterion, e.g. R90C90, for both higher and lower stress levels; R90C90 can be calculated with various methods, and one of these methods will be provided in next Section.
5. Use the Y_0 , which has longer distance to the mean curve, to construct a design curve that parallels to the mean curve;

6. Extrapolate the design curve to the service stress X_S to obtain the predicted life Y_{0S} and compare Y_{0S} with the designed life Y_D ;

7. If the predicted life Y_{0S} is higher than the design life Y_D , the design is approved; Otherwise, a new iteration of design is required.

For a failure process with two or more failure modes, the Bonferroni inequality can provide a conservative accelerated testing solution by evaluating the lower bound [10].

Sample size is an important issue in accelerated testing. Several sample size determination formulae have been given in Nelson's book [3]. The minimum number of specimens required in fatigue S-N tests depends on the types of test program conducted. The sample size for general test has been documented in the ASTM standard [11], see Table 1 in the Appendix, mostly on coupon level test for test data generally showing a linear trend against stress. For fatigue S-N curve with two bilinear curves, i.e. a sloped curve and a horizontal fatigue limit curve, the sample size can be as small as 14 data points [12, 13].

Vehicle testing is much more complex and can be generally divided into several levels such as vehicle level, system level, subsystem level, component level, etc. Different test types require different sample size, and sample size may vary in different design phases for a specific product. SAE Handbook [14] presents such an example on test planning and sample size used in design and development of radius arm pivot bracket for a suspension system. The total design and validation process consists of four phases and each phase allocates specific sample size to meet the cost, timing, and accuracy needs: (a) second redesign proposal (Baseline) with sample size of 3; (2) intermediate design with sample size of 4; (3) optimal design - final prototype level-minimum thickness with sample size of 8; (4) production sample mean thickness with sample size of only 1. The common test sample size for automotive exhaust products are listed in Table 2 of the Appendix. Because of high cost of testing and timing limitation, only very limited sample size (≤ 12) are used. How to obtain reliable information from the limited test data has been a challenge issue for a very long time. Advanced data analysis tools must be developed and used.

TEST DATA ANALYSIS

Data analysis capability is vital to successful durability and reliability engineering designs. Test data roughly consists of two types [3]: (1) performance data, which consists of time domain analysis or frequency domain data, and (2) life data, which can be further divided into several types such as complete data, censored data, multiply censored data, competing modes. Test plan for data analysis with complete life data is the main focus of this paper. Performance data, such as RLDA data for damage calculation with the help of rainflow counting or other cycling counting methods can be found elsewhere [14].

The basic characteristics of life data includes mean, scatter, homoscedasticity and heteroscedasticity, skewness (symmetry), kurtosis, and entropy (uncertainty) [3]. Oftentimes, with proper data transformation and linearization, test data can be curve/surface fitted using a distribution function to gain physical understanding and quantitative description. The commonly used continuous distribution functions for durability and reliability data analysis are: normal, lognormal (two or three parameters), Weibull (two or three parameters), extreme value distribution functions. Three parameter lognormal and Weibull distribution, with the introduced threshold parameter besides the mean (or scale) and standard deviation (or shape) parameters, is especially useful in revealing the underlying physical mechanisms such as crack initiation and crack propagation [3, 15], and the threshold value of standard deviation [15].

Many types of powerful data analysis software are commercially available for engineering applications. However, physical understanding of the data nature is the most important part of a data analysis process. A substantial insight into the data analysis process can also help to properly utilize the advanced software and make a reasonable and correct judgment. The following three fundamental aspects of data analysis will be discussed: the equilibrium method to obtain a mean curve, the design curve construction method, and the Bayesian statistics approach to increase the prediction accuracy and reduce the sample size.

Equilibrium Data Analysis Method

Linear data analysis is often used in engineering applications and has been standardized [11]. Recently, the standard data analysis method has been critically reviewed and a new equilibrium based data analysis method has been developed [16]. Based on the equilibrium method, the identification of data pattern is added as an indispensable pre-processing procedure before any data analysis can be conducted. The equilibrium can also serve as a criterion for visually examining the goodness-of-fit of fit curves [16].

Data fit parameters are usually obtained using the least squares (LS) method or the maximum likelihood estimations (MLE) [17]. Some conventions are made in data analysis, for example, in the ASTM standard for metallic fatigue [11], the stress range is defined as the independent variable because stress range is the "controlled" variable in experiments, and the cycle to failure N is considered as the dependent variable. It is also recommended in the ASTM standard [11] that the cycle to failure N be plotted on abscissa while the stress range S is plotted on ordinate. Therefore, the horizontal offset method is used to evaluate the variation of cycles to failure N [11]. However, the standard method is not universally applicable to all of test data and the drawbacks of the standard method have been indicated [16]. Sometimes, the inaccuracy of the fit curves are obvious but the reason behind it is often not easily discernable because the LS and the MLE methods are abstractive and it is difficult to make a judgment on if the obtained fit parameters and curves are accurate or

not even though both methods are simple and elegant [17]. Therefore, a model with a physical analogy should be very helpful in understanding the data fitting nature and subsequent engineering designs. The following spring model has been proposed for this purpose [16]. In this spring model, each test data point is treated as a mass connected with a massless, frictionless, unbreakable, zero initial length and infinitely stretchable spring, Fig.2. The linear elastic relationship of the springs can then be described by the Hooke's law. Therefore, the force is proportional to the displacement of a spring from its equilibrium position and the mass itself does not make any contribution because static equilibrium is assumed. The best fit curve can then be solved by introducing equilibrium (both linear and angular) concept, which is analogous to the equilibrium of force and angular moments in the classic mechanics. The formulae derived from the equilibrium method are exactly the same as that obtained from the LS method, however, much more information, such as equilibrium direction and data pattern, can be provided using the equilibrium method [16].

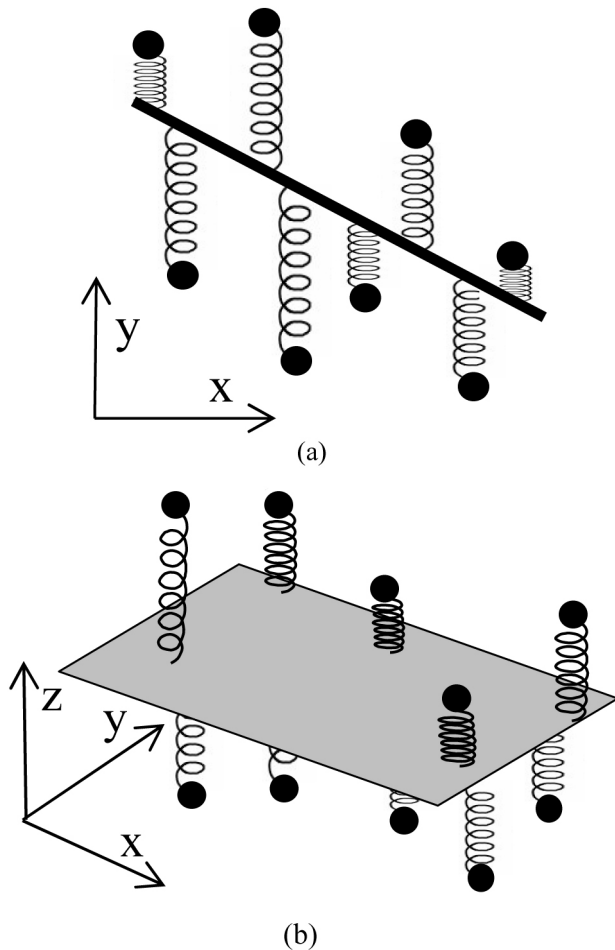


Figure 2. Data points and their elastic spring analogy for (a) curve fitting and (b) surface fitting

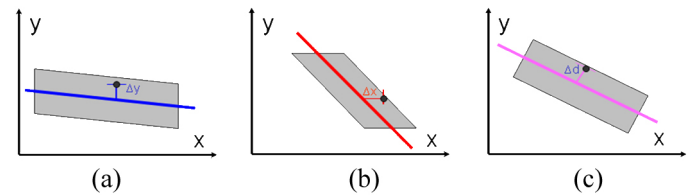
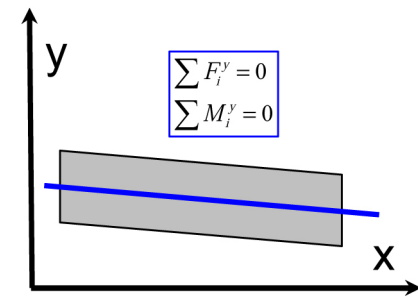
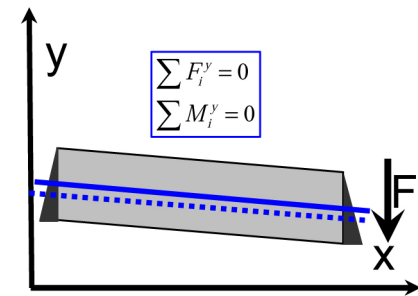


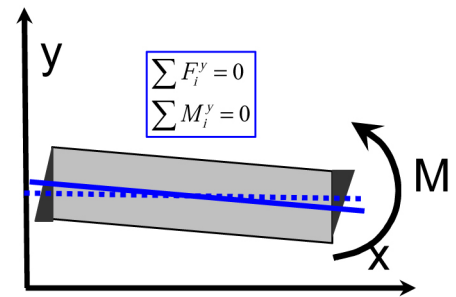
Figure 3. Standard data patterns (a) vertical, (b) horizontal and, (c) perpendicular



(a)



(b)



(c)

Figure 4. Equilibrium establishment of (a) vertical pattern; (b) vertical patterned data with added symmetrical data blocks; (c) vertical patterned data with added anti-symmetrical data blocks

With the equilibrium method, three 'standard patterns', i.e. vertical pattern, Fig.3(a), horizontal pattern, Fig.3(b), and perpendicular pattern, Fig.3(c), have been identified [16]. For data sets with these patterns, based on the equilibrium mechanism, the best fit curve/surface must be the middle curve (line)/middle surface (plane), so that the data can be symmetrically distributed around the expected curve/surface