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Estimating probabilistic fatigue of Nitinol with scarce samples

Palaniappan Ramu [a,*], Sivasankar Arul [b,1]

[a] Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India
[b] Universitat Politècnica de Catalunya, Spain

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ABSTRACT

Current work estimates probabilistic fatigue life efficiently with scarce samples. The underlying idea of the estimation is to approximate the cumulative distribution function of the fatigue life in a transformed space using a third order polynomial subject to monotonicity constraint. The variations associated with the estimated quantiles are quantified using bootstrap. The proposed approach is validated on a data obtained from literature. It is observed that the life quantiles with reasonable accuracy can be estimated even with 10 samples. Finally, the probabilistic fatigue of Nitinol in austenitic condition is obtained with limited experiments.

1. Introduction

Stress-life (S-N) or strain-life (ϵ-N) curves used to characterize fatigue are obtained experimentally and often exhibit scatter in the estimated fatigue lives [1]. This scatter can be contributed by several factors such as surface roughness, residual stresses, variation in distribution of micro-cracks, impurities, orientation of grains etc. In the context of design, a conservative estimate of the fatigue life is usually used. This serves as a safety factor to account for the scatter. However, such an approach leads to over design that translates into increase in cost. Instead, it is desirable to have a band of S-N curves so that based on the criticality of the application, the life values can be chosen.

One method to describe the scatter in fatigue lives is the probabilistic S-N band (P-S-N) [1]. Statistical evaluation of the experimental data allows finding the probability that a proportion of specimens would fail given a load and number of cycles. Traditional S-N curve without any associated probability represents the curve that has 50% probability of failure. Hence, during material selection based on fatigue lives, [2] recommends using the full range of fatigue lives rather than the 50% curve.

A P-S-N band can be visualized as a family of S-N curves each representing a different proportion of specimens that might fail. Traditionally, researchers assume that the scatter follows a log-normal distribution [2–4] and there are standards that advocate the same [5]. Ling and Pan [4] observe that log-normal distribution of life is not appropriate because it provides a decreasing failure rate for long lives. Weibull and Lambda distributions were also used to characterize the fatigue scatter [6–11]. Algorithms using concepts such as conditional probability and Poisson spatial statistics [12–15] were also developed. Murty [16] note that as the number of cycles to failure increases, the reliability decreases and hence conclude that it might not be enough to design only for strength but reliability needs to be accounted. Since it is not possible to establish the band using the physics of the problem [17], a statistical distribution assumption is usually made to bypass the need to test numerous samples. However, selection of a wrong distribution might result in erroneous results. DuQuesnay and Underhill [18] studied the scatter of fatigue life of different aluminum alloys and compared it with the design requirements set by various standards. They noted that a particular class of aluminum alloy exhibited peculiar bimodal life scatter which were not exhibited by other aluminum alloys. Hanaki et al. and Zhao et al. [15,17] have discussed approaches to characterize P-S-N band with limited samples.

As discussed above, a statistical distribution assumption is widely used while estimating the probabilistic fatigue. [11] observes that there is no universally admitted distribution family to model fatigue life. In addition, as [19] points out, the scatter

* Corresponding author at: 314, Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India. Tel.: +91 4422574738; fax: +91 4422574732.

E-mail addresses: palramu@iitm.ac.in (P. Ramu), sivasankar7392@gmail.com (S. Arul).

[1] Formerly at Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India.

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could take different forms and it is desirable to approximate it using a non-parametric approach. Jahn and Maennig [20] approximate the relationship of logarithm of fatigue life, log(N) and its probability (or Cumulative Distribution Function) in transformed space as linear. The probability is empirically estimated as plotting positions and they present different formula for finding the plotting positions.

Estimating probability is equivalent to estimating quantiles. The current work proposes an approach to estimate the quantiles with scarce samples (fewer experiments). The approach named log-Third order Polynomial Normal Transformation (log-TPNT) [19] approximates the Cumulative Distribution Function (CDF) of fatigue lives using a cubic polynomial. A cubic polynomial is used to impose monotonicity of the CDF, in a probit space. It is important to note that the method does not assume any statistical distribution. We also propose providing the confidence interval of the quantile estimates using bootstrap.

Though probabilistic fatigue of many metals has been reported, the same for shape memory alloys (SMA) such as Nitinol is not prevalent in literature. The proposed approach is first demonstrated on data for steel obtained from literature. It is shown that estimation of fatigue life band with associated confidence interval is possible with scarce samples of the order of 10. Next, we use the proposed approach to find the probabilistic fatigue of Nitinol. Behavior of Nitinol depends whether it is cycled under martensitic conditions or under austenitic conditions [21]. The proposed log-TPNT approach is generic in nature, operates only on the fatigue data and can be applied to any condition. However, the results presented in the current work are applicable only for austenitic Nitinol.

The rest of the paper is organized as follows: Section 2 discusses SMA in the context of fatigue. The log-TPNT approach is presented in Section 3. Section 4 demonstrates the approach on fatigue data from literature and to estimate the probabilistic fatigue for Nitinol followed by conclusions.

2. Fatigue studies in SMA

SMAs have the unique property of returning back to their original shape when heated from their deformed state. This property makes them a possible alternative to conventional actuators and many such applications. Since the alloys operate by alternate contraction and elongation they are subjected to fatigue. Fatigue life of SMA depends on many external parameters such as strain, temperature and internal factors such as material composition and heat treatment. Since there are uncertainties associated with each of these factors, the reliability of the shape memory alloys gets affected.

During cyclic loading of SMAs, they are subjected to structural and functional fatigue. Structural fatigue is similar to fatigue failure of regular materials. They also undergo a decrease in the thermo mechanical properties during cyclic loading which leads to functional fatigue. The extent of memory effect that the SMA will display is based on the number of load cycles it can withstand. Hence, fatigue life prediction of SMA is essential in order to ensure their structural integrity during their utility period. Van Humbeeck [22] presents a review of non medical applications where SMA is widely used. They note that the commercial utilization of many concepts can be considered if the service life of SMA under cyclic loads can be established. There are several other researchers

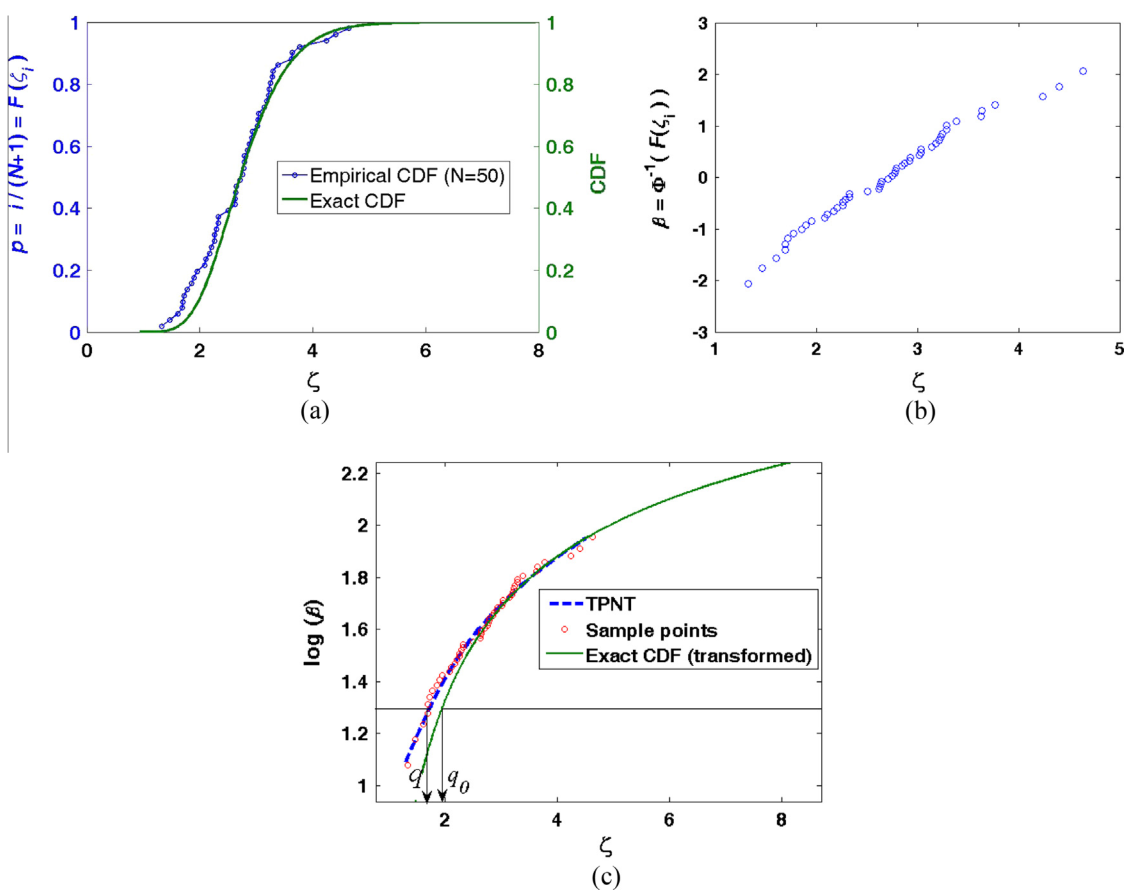

Fig. 1. Proposed log-TPNT approach demonstrated on Lognormal distribution (1, 0.25). (a) Empirical CDF ($N = 50$) and Exact CDF. (b) Ordinate of empirical CDF in (a) transformed using Eq. (2). (c) TPNT fit to data in the log β ordinate. q and q_0 indicate the 10th quantile (~1.31 in the transformed coordinate) for the TPNT fit and the Exact CDF respectively. In order to avoid complex numbers, before applying the logarithmic transformation, the ordinates are offset by 5.