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Reliability-based condition assessment of in-service bridges using mixture distribution models

H.W. Xia [a], Y.Q. Ni [a,*], K.Y. Wong [b], J.M. Ko [a]

[a] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Bridges and Structures Division, Highways Department, The Government of the Hong Kong Special Administrative Region, Hong Kong

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ABSTRACT

Integrating structural health monitoring (SHM) data with reliability analysis procedures provides a novel approach for bridge condition assessment since reliability is an important performance measure of structural condition and reliability-based procedures have the capability of accommodating uncertainties in measurement data. Because the strain response acquired from a bridge under in-service environment is usually a result of multi-load effect such as traffic (highway, railway, or both of them) and wind (monsoon or typhoon), it cannot be characterized by a standard probability distribution model adequately. In the present study, a reliability-based approach to structural condition assessment using mixture distribution models is proposed. With the Weibull distributions being the component density functions, the expectation maximization (EM) algorithm in conjunction with the Akaike information criterion (AIC) is implemented for iterative solution of the optimal number of components and the parameters in finite mixture modeling of peak stresses which are derived from long-term strain monitoring data. Because of using the mixture distribution models, the proposed method is capable of handling monitoring data of any structure and accurately evaluating the reliability indices of monitored structural components. In the case study, the proposed method is applied to assess the in-service structural condition of the deck trusses of the instrumented Tsing Ma Bridge (TMB) under various load combinations such as monsoon, typhoon, with and without railway traffic; and the efficiency of the finite Weibull mixture model for characterizing the statistical properties of peak-stress data with multiple engendering effects and the convergence of the EM-based iteration algorithm for model estimation are validated.

1. Introduction

Condition assessment of in-service bridge structures becomes an increasingly active field driven in part by the need for efficient management of these public assets [1–3]. Data available in the conventional practice of bridge condition assessment generally come from visual inspection, which have been proved to be limited and subjective. In addition to the inspection procedures, a strategy of integrating bridge condition assessment and structural health monitoring (SHM) is deemed to be a valuable practice in this field. The most challenging issue in implementing this strategy is how to develop an objective-oriented method to effectively process and interpret the monitoring data. A number of methods of incorporating SHM data into reliability techniques for the purpose of bridge condition assessment have been developed in recent years [4–9]. The reliability-based condition assessment methods are capable of accommodating the uncertainties in response- and resistance-related parameters and in long-term monitoring data [10–15].

SHM can provide plentiful information about the condition of in-service bridge structures and insights into actual behavior of the bridges under in-service environment. In practice of bridge monitoring, the most common measurands include strain, displacement and acceleration responses of the target bridge. The capability of measuring strain response of a bridge during its operation is particularly meaningful to bridge owners and engineers for a variety of reasons. The measured strain data and their derived stresses can be directly used to indicate fatigue or yielding of the material, safety reserve or reliability of a structural component, and to provide information on the load-carrying capacity of a whole bridge [16–19]. As a typical local response, strain measurement would be better suited to characterize the local behavior and damage of a bridge than displacement and acceleration data.

Inference of a probability distribution function (PDF) from measured strain (and stress) data is necessary to evaluate the elementary reliability indices. In the current reliability-based condition assessment methods, a standard probability distribution model is assumed to characterize the statistical properties of the obtained strains/stresses with the model parameters being estimated from the monitoring data. Making use of long-term strain monitoring

* Corresponding author. Tel.: +852 2766 6004; fax: +852 2334 6389.
E-mail address: ceyqni@polyu.edu.hk (Y.Q. Ni).

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data, Catbas et al. [6] evaluated the reliability of the hanger elements in a truss bridge by defining the limit state function in terms of strain and approximating the strain data in a normal distribution. By converting the measured strains into stresses, Frangopol et al. [7] carried out reliability assessment for the truss members in a highway bridge by defining the limit state function in terms of stress and assuming a normal distribution of the measurement-derived stresses. Using directly measured stresses by elasto-magnetic sensors, Hosser et al. [8] assessed the reliability of the tendons in a pre-stressed bridge deck section by assuming that the stress data conform to the Gaussian distribution. Liu et al. [9] adopted the Gumbel distribution to characterize the measured maximum stress sequences in evaluating the safety of an existing bridge. In reality, however, the strain/stress data acquired from a bridge under in-service environment is usually a result of multi-load effect such as traffic (highway, railway, or both of them) and wind (monsoon or typhoon) [20]. The presence of multiple engendering effects leads to a heterogeneous data structure and makes any standard distribution model inadequate [9].

In the present study, a reliability-based approach to structural condition assessment using mixture distribution models is proposed and validated using the long-term strain monitoring data from the instrumented Tsing Ma Bridge (TMB) carrying both highway and railway traffic. The mixture distribution models are capable of characterizing either single- or multi-modal PDFs, thus making the proposed method applicable to monitoring data of any structure. Because of extensive adaptation capability, the Weibull distributions are selected as the component density functions for finite mixture modeling of peak stresses which are derived from strain monitoring data after eliminating stress-irrelevant temperature effect with a wavelet-based multi-resolution decomposition technique. Iterative solution expressions by the expectation maximization (EM) algorithm are explicitly obtained and applied in conjunction with the Akaike information criterion (AIC) to determine the optimal number of components and the parameters in the finite mixture model. Making use of the field monitoring data from the TMB, the efficiency of the finite mixture model and the convergence of the EM-based iteration algorithm are validated. The reliability indices of the bridge deck members under various load combinations (monsoon, typhoon, with and without railway traffic) are evaluated by the proposed method.

2. Reliability analysis using mixture distribution models

2.1. Mixture distribution models

Inference of a probability distribution from observed data becomes complicated in the presence of multiple engendering effects. In general, the probability distribution of response data due to multi-load effect has a complex geometry and cannot be characterized by a standard probability distribution model adequately. Alternatively, finite mixture distributions which consist of a weighted sum of standard distributions offer a flexible tool in modeling the statistical properties of measurement data with a heterogeneous population and multimodalities [21,22]. For a random variable X, the mixture distribution models decompose its probability density function $f(x|\boldsymbol{\Theta})$ into the sum of m class probability density functions $f_j(x|\boldsymbol{\theta}_j)$ $(j = 1,\ldots,m)$ with the expression

$$f(x|\Theta) = \sum_{j=1}^{m} a_j f_j(x|\theta_j) \quad (1)$$

where $\boldsymbol{\Theta} = \{a_1,\ldots,a_m;\boldsymbol{\theta}_1,\ldots,\boldsymbol{\theta}_m\}$ is the overall parameter vector and each component density function is parameterized by the vector $\boldsymbol{\theta}_j$ $(j = 1,\ldots,m)$. The proportion a_j can be interpreted as the prior probability of observing a sample from class j. The prior probability a_j for each class distribution must be nonnegative and sum-to-one. That is

$$a_j \geqslant 0 \quad \text{for} \quad j = 1,\ldots,m \quad (2)$$

and

$$\sum_{j=1}^{m} a_j = 1 \quad (3)$$

Correspondingly $f_j(x|\boldsymbol{\theta}_j)$ is interpreted as the posterior probability distribution or conditional probability distribution. Through an appropriate choice of its components and weights, a mixture model is expectedly able to model quite complex distributions.

In the selection of elementary distributions for the mixture, a significant and practical simplification can be achieved if all components are of the same type. Although simplified loathly, this approach can recuperate its rationality if the parametric structure of the component density could model a variety of shapes. In this study, the Weibull distribution family is selected as the component density functions because of its adaptability in modeling complicated shapes [23], and in the case study later the efficiency of the finite Weibull mixture model will be compared with the mixture models which adopt the normal and lognormal distributions as the elementary components respectively. The two-parameter Weibull distributions can attain different shapes through various values of the parameters β (shape) and θ (scale) in the expression

$$f_j(x|\boldsymbol{\theta}_j) = \frac{\beta_j}{\theta_j}\left(\frac{x}{\theta_j}\right)^{\beta_j-1} \exp\left\{-\left(\frac{x}{\theta_j}\right)^{\beta_j}\right\}, \quad (4)$$

where β_j and θ_j stand for Weibull shape and scale of the component densities $f_j(x|\boldsymbol{\theta}_j)$ $(j = 1,\ldots,m)$. The adaptability of the Weibull distribution family to different shapes is shown in Fig. 1.

2.2. Model estimation

The parameters a_j and $\boldsymbol{\theta}_j$ $(j = 1,\ldots,m)$ are unknown and must be estimated from observed data. In addition, how many components in the model are not known *a priori* and it must be estimated from the data as well. In a sense the most fundamental parameter in definition of a finite mixture model is the number of components. Its importance results partly from technical considerations that without knowing the component number the process of mixture distribution estimation cannot go further. One approach for obtaining the optimal number of components is to minimize the log likelihood function with the use of AIC [24]. The AIC is expressed as [25]

$$AIC = -2L_n(\boldsymbol{\Theta}) + 2k \quad (5)$$

where $L_n(\boldsymbol{\Theta})$ is the log likelihood, and k is the number of free parameters in the mixture model. The model with a minimum AIC value is chosen to be the best model.

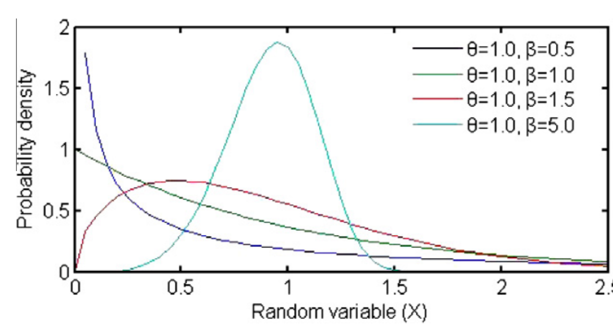

Fig. 1. Weibull distribution family.