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Impairment localization and quantification using noisy static deformation influence lines and Iterative Multi-parameter Tikhonov Regularization

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ABSTRACT

Bridge structures decay throughout their lives even under nominal operating conditions. As bridge infrastructure ages and wears naturally or under extreme load, there is a need to monitor and evaluate bridge performance in an efficient way. This paper presents an impairment detection method that assesses the curvature of noisy static deformation influence lines to predict the location and severity of structural damage. In this method, a parametric approximation and two direct regularization methods i.e., Tikhonov Regularization (TR) and the proposed Iterative Multi-parameter Tikhonov Regularization (IMTR), are implemented to reduce the impact of measurement noise on flexural rigidity estimations. While the TR method assumes one regularization parameter for all unknowns of the optimization problem, the IMTR method has individual, iteratively optimized, regularization parameters for each unknown. To evaluate the performance of the presented method, four nominally identical beam structures with four different damage scenarios and multiple levels of measurement noise are studied. Combining the quadratic spline parametric approximation with either direct regularization method produces adequate curvature estimates that are subsequently used to predict the location and severity of damage. In cases of deep, sharp damage, the IMTR method improves the prediction performance by reducing percent error 4–32%, for noise levels ranging from 0% to 5%, when compared to prediction results from the conventional TR. Both regularization methods give comparable results for shallow, wide damage. A laboratory experiment is included that presents the FRE on a statically indeterminate system; both TR and IMTR provide reasonable estimations of the location and severity of damage.

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1. Introduction

Bridges may deteriorate structurally over time in typical service conditions. Structural impairment detection and assessment is a significant challenge to infrastructure managers. In an effort to monitor, evaluate, and maintain aging infrastructure, many research efforts have resulted in the development of the field of structural health monitoring (SHM) [28,11,31,41,14,33,29,10]. A robust SHM algorithm should be able to provide information that may include impairment existence, location, severity, and remaining service life of a structure [28]. The performance of each individual SHM algorithm is

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dependent on its assessment metric or damage index. Generally speaking, damage indices are defined based on: (1) dynamic responses [11,14,10,3,12,42,43,50], and (2) static responses [39,38,44,45,34,35,46,49]. Generally, static and dynamic methods have strengths and shortcomings. Typically, dynamic sensors (e.g. accelerometers) are easier to install and implement in practice while static sensors (e.g. strain gages, LVDTs) can require significant installation effort. Static deformation measurements may be less affected by noise resulting from transient, incidental vibration or environmental changes and, thus, may relate known load and unknown condition more clearly than noisier dynamic signals [5,9,36].

Recently, static deformation influence lines have been used as an appropriate and robust damage index [38,4,44,45,6,47,49]. Zeinali and Story [49] described the theoretical framework of the relationship between the second derivative of deformation influence line and flexural rigidity in an Euler-Bernoulli beam. This framework is used to calculate the Flexural Rigidity Estimate (FRE) along a beam by quantifying the loading condition and measuring displacement or rotation at one or more locations. In field applications of this method, the rotation or deflection influence line of a specific point is recorded and the resulting RIL or DIL is constructed. In the absence of noise in recorded data, the finite difference method (FDM) is capable of accurately estimating the second derivative of the influence line and FRE equation gives the exact flexural rigidity. However, in practice, measurement errors are unavoidable and the FDM is unable to construct a useful second derivative of noisy data. The FRE framework is a theoretically robust damage index; however, the sensitivity of the method to unavoidable noise in deformation measurements necessitates an analysis method robust against such measurement noise. In this paper, a parametric approximation approach and two direct regularization methods are implemented to fit a smooth curve to the recorded noisy unit load influence line (UIL) and construct an estimation of second derivative of UIL. Using the FRE formula and resultant regularized approximated UIL the flexural rigidity is calculated.

The fundamental idea of the regularization method, used to solve the approximation problem in this paper, is to constrain the solution on the smoothness of the fitted curve. Many direct regularization methods exist: Tikhonov Regularization (TR), Truncated Singular Value Decomposition (TSVD), or Methods of Lines (ML). Among these methods, TR is one of the most common methods and is selected for use in this paper [20,30,37].

Theoretically, TR method is able to solve ill-posed parametric curve fitting problems; however, the regularized results achieved by this method can be improved. To increase the performance of the regularization method, an Iterative Multi-parameter Tikhonov Regularization method is presented and applied to an influence line based impairment detection problem (i.e. FRE estimation). The Iterative Multi-parameter Tikhonov Regularization (IMTR) method is adapted from Tikhonov Regularization in which, instead of using one parameter, a vector of regularization parameters is utilized; each unknown of equation has its individual regularization value.

This paper presents the details of the UIL approximation and subsequent TR and IMTR methods and demonstrates the robustness of the approach through impairment detection using a beam with five damage case scenarios and different noise levels. Both TR and IMTR methods are applied on this noisy UIL data and the results of comparisons are presented. An application of the presented methods for FRE of an indeterminate system in laboratory is also detailed.

2. General framework for flexural rigidity estimation (FRE)

Zeinali and Story [49] presented a theoretical framework, in which, by utilizing the static deformation influence lines the flexural rigidity of Euler-Bernoulli beams could be estimated. In the proposed flexural rigidity estimate (FRE) formula, the relationship between the second derivative of deformation influence line and the flexural rigidity for both statically determinate and indeterminate beam structures is presented as:

$$EI(x) = \frac{m(x)}{u''_{x_0}(x)} \tag{1}$$

In Eq. (1), $u''_{x_0}(x)$ is the second derivative of rotation or deflection influence line (RIL or DIL, respectively) at a specific point (x_0), $EI(x)$ is the flexural rigidity of the cross-section at location x, and $m(x)$ is the resultant internal moment caused by a unit load (in case of using *DIL*) or a unit moment (in case of using *RIL*) applied at location of measurement point x_0.

This equation can be achieved by using classical notion of static Green's function.

Consider that the response of a structural system to load patterns p or $\hat{p}$ are u, or $\hat{u}$, respectively. Betti-Maxwell's theorem express that work done by load pattern p on the displacement $\hat{u}$ is equal to the work done by the load pattern $\hat{p}$ on the displacement u. This theorem can be expressed based on Green's second identity as [21]:

$$\mathcal{B}(u, \hat{u}) = \mathcal{G}(p, \hat{u}) - \mathcal{G}(\hat{p}, u) = 0 \tag{2}$$

In Eq. (2), $\mathcal{G}$ presents the work done by its first argument due to displacement of its second argument.

Assume that the system under consideration is a simply supported beam with span length of L and a moving unit load passing over, as depicted in Fig. 1. In this figure, ξ is the location of moving unit load from support A. So, the term $u_{x_0}(\xi)$ is the beam deflection at location x_0 when unit load is applied at distance ξ. The complementary system to this main system is a beam with the same boundary conditions but a unit load applied at the measurement point at location x_0. Using the same notation, the beam deflection at location ξ on this complementary system can be represented by $u_\xi(x_0)$. Because the applied loads are just a single unit load, then the results of the Betti-Maxwell's theorem can be simplified as:

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