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Strain response estimation for the fatigue monitoring of an offshore truss structure

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Abstract

Fatigue damage accumulation is an outstanding issue in ocean engineering due to long-term cyclic mechanical behaviours resulting from wind, waves and currents. Fatigue monitoring of offshore truss structures has been limited by the costs and techniques of current strain sensors. Aiming to estimate the unmeasured response of structural members, for which there are no available sensors, this paper proposes a strain response estimation strategy using three types of state-space formulations and a Kalman Filtering (KF) process. A strain modal coordinate based state-space model was developed, especially for large engineering structures. The theoretical approaches were evaluated using the numerical simulations based on deterministic and stochastic excitations. The algorithm can be integrated with the existing fatigue monitoring system as an early warning tool.

Keywords: Strain response estimation; Offshore truss structure; State-space formulation; Kalman filtering; Fatigue monitoring

Introduction

As an orderly hinged system, the truss structure has been used extensively in ocean engineering, e.g., offshore jacket platforms, wind turbines, deepwater truss spar platforms, pipe laying vessels and attached facilities. As is known to all designers and engineers, environmental loads, such as wind, waves and currents, act on the platform and the subsystems, resulting in long-term cyclic responses and fatigue damage accumulation. Fatigue monitoring of the offshore truss structure is still as significant an issue as the riser VIV, especially related to the coupling effect of the corrosion. However, the use of fatigue monitoring has been limited due to the high costs and the available practical techniques; as a result, the sensor network can hardly cover the key parts of the offshore truss structures, including vulnerable underwater locations. Therefore, it is essential to determine a feasible method to estimate the unmeasured response of the structural members in locations where there is no available sensor.

Optimal State Estimation has been developed since the sixties of the last century [1]. Systematic state variables can be statistically inferred and quickly approach the true values using the state-space formulation and the KF (and other advanced) process. The

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maximised amount of information can be extracted from the measured vibration signals in mechanical and structural systems based on both time and observational updating. Specifically, KF allows for the estimation of an unmeasured response based on a given sparsely measured time history response and a model of the system [2,3]. A first-order state-space formulation in structural and mechanical systems can be built through FEMs and the state variables, such as the displacement and stress/strain.

Within the scope of the present paper, the unmeasured responses of the structural members for which there is no available sensor must be estimated, and all of the achieved responses can be utilised for fatigue evaluation. Papadimitriou et al. (2010) proposed fatigue life predictions in the entire body of metallic structures from a limited number of vibration sensors using KF [4]. Hernandez et al. (2011) developed an advanced observer as a modified KF for second-order linear structural systems [5]. The approach is used to estimate the number of threshold crossings in the bending moment history of a simulated tall vertical structure subject to turbulent wind [6]. However, the above predictions of fatigue damage accumulation are in terms of the power spectral density (PSD) of the stress processes. A real-time and long-term cyclic tracking of responses must be conducted on practical engineering applications of such theoretical approaches.

Considering that the fatigue monitoring in the ocean engineering area usually use a strain sensor, such as a fibre Bragg grating (FBG) and a linear variable differential transformer (LVDT), this paper focuses on the strain response estimation of the unmeasured structural members in the truss structure using the KF process. Three types of structural state-space formulations are derived for a more practical KF process. Theoretical methods are validated by a simple truss FEM.

Basic method

State-space formulation based on nodal displacement

For the structural dynamics in the finite element formulation with n degrees of freedom (DOFs) and m elements, the differential equation describing the dynamics is as follows.

$$M\ddot{q}(t) + C\dot{q}(t) + Kq(t) = B_0 u(t) + w(t) \tag{1}$$

where $q(t)$ is the n-order node displacement vector; M, C and K are the n-order mass, damping and stiffness matrices, respectively. $u(t)$ is the n-order deterministic load vector; B_0 is the deterministic load input matrix of$n \times n_B$. Generally, the stochastic loads act on all DOFs of the structural model. $w(t)$ is the n-order stochastic load vector that is also called system noise in the control theory.

The state vector is defined as the nodal displacement vector and the nodal velocity vector: $x(t)^T = \{q(t)^T \dot{q}(t)^T\}$. The equations of motion can be expressed as a type of first-order differential form:

$$\dot{x}(t) = Ax(t) + B_u u(t) + B_w w(t) \tag{2}$$

This equation is called the equation of state. The structural finite element model is expressed as the state-space representation:

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix},$$
$$B_u = \begin{bmatrix} 0 \\ M^{-1}B_0 \end{bmatrix}, \quad B_w = \begin{bmatrix} 0 \\ M^{-1}I \end{bmatrix} \tag{3}$$

where A is the system matrix of $2n \times 2n$; B_u is the deterministic input matrix of $2n \times n_B$; B_w is the stochastic input matrix of $2n \times n$; and I is the n-order unit matrix.

The output conversion process is given by the equation of measurement:

$$y(t) = Hx(t) + v(t) \tag{4}$$

where $y(t)$ is the strain response output vector. The finite element is assumed to be some simple linear element, such as the beam element and the truss element, in this study. The structural strain response is defined as the strain along the direction of the finite element length, which yields the m-order vector. H is the measurement matrix of $m \times 2n$; $v(t)$ is the m-order measurement noise vector. Note that only limited measured strain responses can be achieved, so the element is zero in the j-th ($j \in \{1 \cdots m\}$) row of $y(t)$. Meanwhile, the elements in the j-th ($j \in \{1 \cdots m\}$) row of the measurement matrix H is also zero. The singular matrix is written as H_S.

According to the theory of the FEM, the measurement matrix should be derived based on the relationship between the elemental strain and the node displacement. First, in consideration of the element analysis, the shape function matrix of the finite element is set as N. Based on the virtual displacement principle for deformable bodies, the relationship between the internal stain ε_i of the element i and the element node displacement vector $\{q_i^0\}$ in the local coordinate system can be given by,

$$\varepsilon_i = \{DN\}\{q_i^0\}^T \tag{5}$$

where D is a differential operator. Next, the global analysis is performed on the element node displacement vector in the global coordinate system:

$$\beta\{q\} = \left\{ \{q_1^0\} \quad \cdots \quad \{q_i^0\} \quad \cdots \quad \{q_m^0\} \right\}^T \tag{6}$$