FATIGUE LIFETIME PREDICTIONS IN METALLIC STRUCTURES USING LIMITED NUMBER OF VIBRATION MEASUREMENTS

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1. Objective

This work deals with the problem of estimating damage accumulation and predicting the lifetime due to fatigue in the entire body of a metallic structure using output-only vibration measurements from a sensor network installed at a limited number of locations in a structure. The objective is to formulate the problem, present the methods and assumptions under which effective fatigue predictions can be accomplished, outline the main issues and factors that affect the accuracy of the predictions, as well as illustrate the effectiveness of the methods with selected applications using simulated measurements.

2. Introduction

Damage accumulation due to high-cycle fatigue is an important safety-related issue in metallic structures. Methods exist to estimate the damage accumulation at a point in a structure using the response time histories of the components of the stress sensor at the corresponding point. One such method integrates experimentally obtained S-N fatigue curves for damage prediction, Miner linear damage accumulation law accounting for arbitrary stress response time histories, cycle counting per stress level methods in stress response time histories, and methods for handling multi-axial stress states at a point. These methods can be applied to any point in the structure and construct the complete fatigue map of the entire structure, provided that the stress response time histories at all desirable points are available.

The characteristics of the stress response time histories at a point in a structure can readily be predicted by using a model of the structure (e.g. a finite element model) and the actual excitation time histories. However, for most structures, the excitation time histories are neither available nor can be conveniently measured by a system of sensors, while simplified representations of excitation models often used for design purposes do not reflect the actual excitation conditions during various phases of operation of the structure. In addition, the models of the structure may lack the desirable accuracy due to model error. Alternatively, the stress response time histories at a structure can be readily inferred using measurements obtained by placing strain rosettes. Even in this case, there are significant limitations in predicting the stress time histories in the entire body of the structure since the number of sensors in a sensor network is usually very limited and cannot cover all points or critical structural locations. Moreover, structural locations may not be all approachable to place sensors (e.g. hard to reach structural locations in large extended structures, submerged structures, heated structural components, internal points in a structure).

This work concentrates mainly on proposing methods for predicting the characteristics of the stress response time histories in the entire body of the structure using measurements collected from a sensory system placed at limited number of structural locations. Such predictions can be employed for estimating damage accumulation maps due to fatigue. The excitation in the structure during its operation is considered to be unknown. The main assumptions for the proposed predictions are that the structure is linear, the responses are realizations of a stochastic stationary process, and the unmeasured excitations can be modelled by stationary stochastic processes.

3. Methodology

Available frequency domain stochastic fatigue methods based on Miner's damage rule, S-N fatigue cycle curves, and Dirlik's probability distribution of the stress range are used to predict the expected fatigue accumulation of the structure in terms of the power spectral density (PSD) of the components of the stress tensor process [1,2]. Thus, the problem is reduced to estimating the PSDs of the stress components at unmeasured locations using the available measured response time histories at limited locations of the structure. These PSDs of stresses are estimated by using stochastic representations of the excitation models, Kalman filter techniques [3] or kriging methods. The accuracy of the predictions in such methods under unknown stochastic excitations depend highly on the accuracy of the stochastic process models used to represent the uncertain temporal and spatial characteristics of the excitation time histories, as well as the accuracy of the models used to represent the structural behaviour. Model identification methods are proposed to estimate, based on the vibration measurements, reliable stochastic models of the uncertain excitations, as well as update the structural models. In particular, it is demonstrated that optimal sensor configuration strategies are useful tools for improving predictions.

4. Results and Conclusions

The proposed formulation is demonstrated using simulated measurements from (a) an N-DOF spring-mass chain model arising from structures that consist of members with uniaxial stress states and (b) a three-dimensional structure that is modelled by shell/plate elements with bi-axial stress states. The factors that affect the accuracy of the methodology are investigated by comparing the fatigue accumulation results in the entire structure predicted by the proposed methodology with reference fatigue accumulation results. It is shown that the accuracy of the proposed method for fatigue predictions in the entire body of the structure depends on the number and location of sensors in the structures, the number of modes contributing in the dynamics of the structure, the size of the model error and measurement error, and the accuracy of the stochastic excitation models.

The proposed methodology can be used to construct fatigue damage accumulation and lifetime prediction maps consistent with the actual operational conditions provided by a monitoring system. In particular, the stochastic excitation models identified from measurements under various operational states, can also be used with the stochastic fatigue method for lifetime prognosis purposes. The proposed method is useful for designing optimal fatigue-based maintenance strategies for metallic structures using structural vibration information collected from a sensor network.

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6. References

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