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Integration of structural health monitoring and fatigue damage prognosis

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A B S T R A C T

This paper presents a Bayesian probabilistic methodology to integrate model-based fatigue damage prognosis (FDP) with online and offline structural health monitoring (SHM) data. The prognosis uses fracture mechanics-based fatigue crack growth modeling, along with quantification of various sources of uncertainty, including natural variability, data uncertainty and model errors. These uncertainty sources are connected using a Bayesian network and a probabilistic sensitivity analysis is performed to assess the uncertainty contributions from these sources. The cycle-by-cycle simulation of fatigue crack growth is expedited via the use of a surrogate modeling technique (Gaussian process model) to replace computationally expensive finite element analysis. Real-time monitoring data of external variable amplitude loading history is used to construct a Bayesian autoregressive integrated moving average (ARIMA) model to predict and update the loading. On-ground crack inspection data is used to quantify the uncertainty in the initial and current size of an existing crack, using the Bayesian approach. Three possible cases of inspection results are considered: (1) crack is not detected; (2) crack is detected but not measured; (3) crack is detected and measured. Different scenarios of data availability (load monitoring data and inspection data) are considered for the prognosis of an individual component in a fleet. A numerical example, surface cracking in a rotorcraft mast under service loading, is implemented to illustrate the proposed methodology. The results of prognosis are validated using Bayesian hypothesis testing.

1. Introduction

Accurately estimating the remaining useful life (RUL) for aging aerospace mechanical components under fatigue loading has been a challenge due to the complexity and uncertainty in service environments and multidisciplinary damage mechanisms. The emerging techniques in both the areas of structural health monitoring (SHM) and fatigue damage prognosis (FDP) provide a promising future for tackling this challenge. Note that SHM and FDP are connected in nature, and a robust FDP relies on knowledge of the current status of components and service environment monitored by SHM system. Hence, in addition to the extensive research efforts conducted separately in SHM and FDP, integration of these two technologies is desired [1].

Based on the sensor-monitored data of external loading applied on mechanical components, different methods have been used to characterize and predict loading for fatigue damage prognosis, including rainflow counting [2], the Markov chain method [3], and ARMA (autoregressive moving average) modeling [4], etc. The authors of this paper have extended

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Nomenclature

ARMA	autoregressive moving average
ARIMA	autoregressive integrated moving average
CSM	crack size measurement
EIFS	equivalent initial flaw size
FCP	false call probability
FDP	fatigue damage prognosis
FEA	finite element analysis
GP	Gaussian process
HUMS	health and usage monitoring system
LEFM	linear elastic fracture mechanics
NDI	non-destructive inspection
OLM	operational loads monitoring
POD	probability of detection
PSA	probabilistic sensitivity analysis
RUL	remaining useful life
SHM	structural health monitoring
SIF	stress intensity factor

the ARMA modeling method to account for various uncertainty sources in service loading and developed a Bayesian approach to update the ARMA model with real-time monitoring data [5]. On-ground damage inspection for aerospace mechanical components using non-destructive inspection (NDI) techniques includes crack detection and size measurement. Different techniques using crack size measurement (CSM) data to infer the probability distribution of an equivalent initial flaw size (EIFS), which is the starting point of fatigue crack growth analysis, have been developed [6–8], including Bayesian approaches to account for multiple sources of uncertainty [8,9].

In the area of FDP, numerous fracture mechanics-based crack propagation models have been proposed to analyze the behavior of metal fatigue, and a summary of these models can be found in [10]. Due to the stochastic nature of fatigue crack growth, a probabilistic prognosis method is desired. Studies have been conducted on probabilistic damage prognosis accounting for physical variability [1,11,12]. In a recent paper, we have developed a detailed uncertainty quantification approach for fatigue crack growth modeling that includes physical variability, data uncertainty and model uncertainty [13].

The purpose of this paper is to develop a probabilistic methodology to integrate SHM results into a fracture mechanics-based FDP for aerospace mechanical components in a fleet, accounting for various sources of uncertainty and errors.

First, uncertainty quantification approaches for SHM and FDP are investigated. Two types of SHM data – real-time load monitoring data and on-ground crack inspection data – are considered, and the uncertainty due to the monitoring technique is quantified in Section 2. In Section 3, crack growth prognosis for mechanical components with realistic geometry and subjected to multi-axial variable amplitude loading is presented, with a focus on uncertainty quantification. Various sources of uncertainty and errors in prognosis are quantified, including physical variability in loading and material properties, data uncertainty due to the use of the structural health monitoring data and insufficient data, and model uncertainty and errors due to the use of various models in prognosis (crack growth model, loading model, finite element discretization error, etc.). A Bayesian network is constructed to systematically integrate the various uncertainties and errors, and a global sensitivity analysis is performed to identify the contributions of these sources to the uncertainty in the prognosis results (the predicted crack size after a number of loading cycles).

Section 4 proposes a framework to integrate SHM data with FDP. The fatigue loading sequence is characterized and predicted using an ARIMA (autoregressive integrated moving average) modeling method based on real-time load monitoring data. A Bayesian updating approach is used to estimate the coefficients of the ARIMA model and a probabilistic model averaging method is used to account for load model uncertainty. The probability distributions of EIFS and current crack sizes are inferred from the on-ground crack inspection data via a Bayesian method. The application of this integrated framework is shown for both individual components and a fleet of components. Sometimes it may be expensive to implement load monitoring and comprehensive inspection for the entire fleet. Only some of components may be selected for load monitoring and detailed examination, including crack detection and measurement, and the health status of the other components may have to be inferred combining existing data and model based-prognosis. Strategies of FDP for components in the fleet with different monitoring status are proposed. The prognosis results are validated using a Bayesian hypothesis testing method when new crack inspection data become available. A numerical example is presented in Section 5 to illustrate the overall framework of integrating prognosis with structural health monitoring under uncertainty.

2. Structural health monitoring under uncertainty

Both real-time load monitoring and on-ground crack inspection are considered in this paper since they are directly relevant to fatigue damage prognosis (FDP) for aerospace mechanical components.

2.1. Real-time load monitoring

The external loading applied on aerospace components is an important input to fatigue damage prognosis. Real-time monitoring of the loads which will be used to estimate the accumulated fatigue damage is commonly known as Operational Loads Monitoring (OLM), which is part of a Health and Usage Monitoring System (HUMS) [14]. Two techniques have been applied to implement OLM, namely flight parameters-based loads monitoring and strain gauge-based loads