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Optimization of nonlinear, non-Gaussian Bayesian filtering for diagnosis and prognosis of monotonic degradation processes

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ABSTRACT

The present work critically analyzes the probabilistic definition of dynamic state-space models subject to Bayesian filters used for monitoring and predicting monotonic degradation processes. The study focuses on the selection of the random process, often called *process noise*, which is a key perturbation source in the evolution equation of particle filtering. Despite the large number of applications of particle filtering predicting structural degradation, the adequacy of the picked process noise has not been investigated. This paper reviews existing process noise models that are typically embedded in particle filters dedicated to monitoring and predicting structural damage caused by fatigue, which is monotonic in nature. The analysis emphasizes that existing formulations of the process noise can jeopardize the performance of the filter in terms of state estimation and remaining life prediction (i.e., damage prognosis). This paper subsequently proposes an optimal and unbiased process noise model and a list of requirements that the stochastic model must satisfy to guarantee high prognostic performance. These requirements are useful for future and further implementations of particle filtering for monotonic system dynamics. The validity of the new process noise formulation is assessed against experimental fatigue crack growth data from a full-scale aeronautical structure using dedicated performance metrics.

1. Introduction

Bayesian filtering algorithms are gaining popularity in many engineering applications and they are emerging as a state-of-the-art technique in the fields of probabilistic life prediction, structural health monitoring (SHM), and prognostics and health management (PHM), especially when the diagnostic-prognostic process requires real-time execution. Among the different classes of Bayesian filters, particle filtering, a sequential Monte Carlo method developed by Gordon, Salmond and Smith [1], is of great interest because of its ability to deal with nonlinear systems characterized by non-Gaussian variables [1–6]. Recent applications of particle filtering have been presented in literature in a number of diagnostic and prognostic scenarios: fault detection in structural components [7,8], prediction of turbine blade creep [9], prediction of lithium-ion battery degradation [10,11] and asymptotic process prediction in composite materials [12]. Literature also provides examples of particle filtering applied in the field of nonlinear structural dynamics and structural parameter identification [13,14]. Other works related to particle filtering are analyzed throughout the paper.

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Nomenclature

C^*	Paris' law parameter
F	crack shape function
K	stress intensity factor
k	discrete time step
k^*	gamma distribution parameter
N	load cycle
N_s	number of samples
n	system state vector dimension
m	measurement vector dimension
m^*	Paris' law parameter
p	input vector dimension
q	model parameter vector dimension
S	remote stress
$\mathcal{U}$	input vector support
$\boldsymbol{u}$	input vector
$\mathcal{X}$	system state vector support
$\boldsymbol{x}$	system state vector
$\mathcal{Z}$	measurement vector support
$\boldsymbol{z}$	observation vector
$\delta_{\cdot,\cdot}$	Kronecker delta
$\boldsymbol{H}$	measurement noise vector support
$\boldsymbol{\eta}$	measurement noise
$\boldsymbol{\Theta}$	model parameter vector support
θ^*	gamma distribution parameter
$\boldsymbol{\theta}$	model parameter vector
μ	mean
Σ	covariance matrix
σ	standard deviation
σ^2	variance
$\boldsymbol{\Omega}$	process noise vector support
$\boldsymbol{\omega}$	process noise vector

The design of the filter includes a random process introduced in the model equation describing the system dynamics. This random process works as a perturbation source describing the inherent, un-modeled uncertainty of the system and is inherent in defining the probability density function (pdf) of the system state variables. Such process noise aims at describing, for example, micro-scale dynamics of the damaging process, which is not accounted for in macro-scale engineering models. In the fields of SHM and PHM, such a random process is often called *process noise*, where the term 'process' indicates the system evolution process, and 'noise' emphasizes its stochastic, perturbative nature. The definition of the process noise is typically made by the algorithm designer, but none of the applications of particle filtering for diagnostic and prognostic of structures presented in literature discusses the efficiency and effectiveness of the chosen random process. This paper will clearly show that this selection does, in fact, have implications on the filter's predictive performance.

In addition to the above-cited papers [7–11], the works in [15–20] are remarkable examples of real-time fatigue crack growth (FCG) prognosis in metallic structures based on particle filtering. Recent works investigating different aspects of particle filtering-based FCG prognosis are also available in [21–23]. Applications of particle filtering for life prediction of composite materials subject to matrix micro-cracking are available in [12,24,25]. All those papers defined the process noise in different ways (some of them using nonlinear non-Gaussian random processes), but none of them discussed the selected process critically.

The analysis presented in this paper shows that if the process noise is not carefully tuned, the algorithm may encounter computational inefficiencies or it might fail the prognostic goal, defined here to be the accurate prediction of the remaining useful life (RUL) of the structure. Indeed, this analysis shows the drawbacks of process noises adopted in previous papers. Then, the paper proposes a process noise to improve the efficiency and effectiveness of particle filtering for monitoring and prognosis of monotonic degradation phenomena. Cracks in metallic alloys, delamination and matrix crack density evolution in composite laminates, and creep-induced plasticity are typical cases of monotonic degradation where particle filtering (if properly tuned) can help in monitoring the damage severity and predicting the RUL. It should be noted that the proposed process noise was already used by the authors in an application of particle filtering for composite materials suffering concurrent damage mechanisms [26]. Nevertheless, a critical analysis of the process noise was not presented in that work. Also, this paper proposes three requirements that the evolution equation, which strongly depends on the process noise, has to satisfy in order to build an efficient Bayesian filtering framework. Eventually, the designed filter is applied