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A functional model based statistical time series method for vibration based damage detection, localization, and magnitude estimation

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ABSTRACT

A vibration based statistical time series method that is capable of effective damage detection, precise localization, and magnitude estimation within a unified stochastic framework is introduced. The method constitutes an important generalization of the recently introduced functional model based method (FMBM) in that it allows for *precise* damage localization over properly defined *continuous topologies* (instead of pre-defined specific locations) and magnitude estimation for the first time within the context of statistical time series methods that use *partial identified models* and a *limited number of measured signals*. Estimator uncertainties are taken into account, and uncertainty ellipsoids are provided for the damage location and magnitude. The method is based on the extended class of vector-dependent functionally pooled (VFP) models, which are characterized by parameters that depend on both damage magnitude and location, as well as on proper statistical estimation and decision making schemes. The method is validated and its effectiveness is experimentally assessed via a proof-of-concept application to damage detection, precise localization, and magnitude estimation on a prototype GARTEUR-type laboratory scale aircraft skeleton structure. The damage scenarios consist of varying size small masses attached to various continuous topologies on the structure. The method is shown to achieve effective damage detection, precise localization, and magnitude estimation based on even a single pair of measured excitation–response vibration signals.

1. Important conventions and symbols

Definition is indicated by $:=$. Matrix transposition is indicated by the superscript T.
Bold-face upper/lower case symbols designate matrix/column-vector quantities, respectively.

Abbreviation: AR, Autoregressive; ARX, Autoregressive with exogenous excitation; BIC, Bayesian information criterion; FEM, Finite element model; FMBM, Functional model based method; FP, Functionally pooled; FRF, Frequency response function; GA, Genetic algorithm; iid, Identically independently distributed; NLS, Nonlinear least squares; OLS, Ordinary least squares; PE, Prediction error; RSS, Residual sum of squares; SHM, Structural health monitoring; SQP, Sequential quadratic programming; SSS, Signal sum of squares; VFP, Vector-dependent functionally pooled; WLS, Weighted least squares; X, Exogenous.

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A functional argument in parentheses designates function of a real variable; for instance $P(x)$ is a function of the real variable x.

A functional argument in brackets designates function of an integer variable; for instance $x[t]$ is a function of normalized discrete time ($t=1,2,\ldots$). The conversion from discrete normalized time to analog time is based on $(t-1)T_s$, with T_s designating the sampling period.

A hat designates estimator/estimate; for instance $\widehat{\boldsymbol{\theta}}$ is an estimator/estimate of $\boldsymbol{\theta}$.

2. Introduction

Damage detection, localization, and magnitude estimation (collectively referred to as damage diagnosis, or damage detection and identification) in vibrating structures, including aerospace, mechanical, civil, and marine structures, are of paramount importance for reasons associated with improved dynamic performance, proper operation, increased safety, and reduced maintenance costs [1–4].

The need for global damage diagnosis has led to the development of methods that focus on detecting changes in a structure's vibration response characteristics as a result of changes in the dynamics caused by damage [2–7]. Most methods typically involve two phases: an initial *baseline (training) phase* which is performed once at outset, and under which the dynamics of the structure under healthy (and perhaps certain damage) conditions are obtained, and an *inspection phase* which may be performed on demand, or periodically, or even continuously in time (online), and under which the current structural dynamics are identified and "compared" in a proper sense to those of the baseline phase in order to achieve damage detection, localization and magnitude estimation.

Vibration based methods may be classified into two main subfamilies: (a) those based on detailed physical or analytical models (such as finite element models, FEMs) describing the complete structural dynamics and (b) those based on statistical time series and related methods. FEM based methods require the use of detailed "large" models, describing the complete structural dynamics, that need to be accurately updated in the inspection phase [3,8–13]. This is not only a burden for the inspection phase, but also an operation requiring a large number of installed sensors and measured signals [3,14,15].

Statistical time series and related methods offer the important advantage of being based on *partial* models of the structural dynamics, which are identified based on a potentially "small" number of vibration signals (sometimes even on a single signal or a single signal pair)—see the survey papers [5,6,16]. They may be thought of as generalizations of earlier techniques using deterministic models and identification techniques—a classical early approach being that of damage detection based on natural frequency changes in modal models [2,7,17]. Statistical time series type methods utilize statistical models and identification techniques that take uncertainties into account, they may operate on normal operating vibration signals, in an output-only mode, and also on structures of any size and geometry [18–23]. They may be thought of as including the related class of statistical pattern recognition type methods [24–29]. While damage detection may be potentially treated effectively by many of these methods, the damage localization problem is typically treated as a *classification problem*, meaning that a damage location is selected among a *finite* number of potential damage locations. This is a simplification, resulting in a much simpler problem than precise damage localization over properly defined *continuous topologies* on a structure – that is to say infinite possible damage locations – which essentially corresponds to the actual SHM problem. Furthermore, damage magnitude estimation is generally not possible (except for maybe some "rough" characterization)—a method offering an approach for properly tackling this problem has been recently introduced by the second author and co-workers [30,31].

The *aim* of the present study is the introduction and experimental validation and assessment of a generalized version of the FMBM which is – for the first time within the context of statistical time series type methods – achieving *complete* and *precise* damage *localization* over *continuous topologies* on a structure, combined with damage *magnitude estimation*. Furthermore, estimator uncertainties are fully taken into account in all phases of the diagnostic procedure, and uncertainty ellipsoids are provided for combined damage location and magnitude. Like the original FMBM, the method utilizes a partial and reduced size identified model, and is capable of operating on a "low" number of measurement sensors – even on a single pair for "small" structures – and any type of vibration response signals (acceleration, velocity, displacement).

The method's cornerstone is the new extended class of *vector-dependent functionally pooled* (VFP) models [32]. These are generalizations of the functional pooled (FP) models of Sakellariou and Fassois [30,33], which now allow for the analytical inclusion of *both* damage location and magnitude on the structural dynamics. VFP models thus allow for the extension of the notion of *damage mode* (fault mode) to include damage not only of all possible magnitudes, but also of all possible *locations* on a specific continuous topology on a structure. As VFP models have a richer structure than their FP counterparts and use bivariate (two-dimensional) polynomials belonging to functional subspaces for parameter projection, functional subspace dimensionality estimation is a more complicated task which is accomplished through a suitable genetic algorithm (GA) based procedure.

The method is validated and its effectiveness is experimentally assessed via a proof-of-concept application to damage detection, precise localization, and magnitude estimation on a prototype GARTEUR-type laboratory scale aircraft skeleton structure [34,35]. The damage scenarios considered include the attachment of varying size small masses to various continuous topologies on the structure. Such added mass "pseudo-faults" are often used in the literature as approximate ways of generating signals corresponding to various fault scenarios; for instance see [36–39]. In any case, the issue of using