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A time series generalized functional model based method for vibration-based damage precise localization in structures consisting of 1D, 2D, and 3D elements

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ABSTRACT

This study focuses on the problem of vibration-based damage precise localization via data-based, time series type, methods for structures consisting of 1D, 2D, or 3D elements. A Generalized Functional Model Based method is postulated based on an expanded Vector-dependent Functionally Pooled ARX (VFP-ARX) model form, capable of accounting for an arbitrary structural topology. The FP model's operating parameter vector elements are properly constrained to reflect any given topology. Damage localization is based on operating parameter vector estimation within the specified topology, so that the location estimate and its uncertainty bounds are statistically optimal. The method's effectiveness is experimentally demonstrated through damage precise localization on a laboratory spatial truss structure using various damage scenarios and a single pair of random excitation - vibration response signals in a low and limited frequency bandwidth.

Important conventions and symbols

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

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.

Abbreviation: ARX, AutoRegressive with eXogenous excitation (model); BIC, Bayesian Information Criterion; FEM, Finite Element Model; FMBM, Functional Model Based Method; FM, Functional Model; FRF, Frequency Response Function; GA, Genetic Algorithm; iid, identically independently distributed; NLS, Nonlinear Least Squares; OLS, Ordinary Least Squares; PSD, Power Spectral Density; RSS, Residual Sum of Squares; SHM, Structural Health Monitoring; SPP, Sample Per Parameter; SSS, Series Sum of Squares; VFP-ARX, Vector dependent Functionally Pooled ARX (model)

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

1. Introduction

Damage localization is one of the important subproblems associated with the broader Structural Health Monitoring (SHM) problem, the others being damage detection, characterization, and magnitude (size) estimation [1–4]. Of these, damage detection is probably the easiest and most well studied [5–8].

In the context of vibration based methods, the damage localization subproblem has been tackled mainly through *analytical model-based approaches*. These use detailed physics-based models of the structural dynamics – typically of the Finite Element type – and may lead to damage localization (mostly in the sense of identifying the damaged structural element) through the use of current vibration signals and model updating procedures. The prerequisites are the availability of a detailed structural model, proper representation of damage, and updating parameters sensitive to the selected measured response(s) [9]. In practice such a procedure typically requires detailed (thus large) FEMs and several vibration sensors for proper model updating [10–12].

Within the context of *data-based approaches* – which use data based models instead of their physics based counterparts – the damage localization subproblem has been tackled as a *classification problem* where the structure is divided into a number of regions or elements, and damage is localized to any one of them [6,7,13–19].

This study focuses on the localization problem within the latter (data-based) class of methods, but from a different viewpoint, posing the question of *damage precise localization*. This implies *estimation* of the damage precise coordinates on the investigated structural topology, assuming that damage may occur *anywhere* on the specified topology. Of course, this is a much more complex problem, but also highly interesting from a methodological and practical point of view.

Past work on the precise localization problem has been carried out by certain of the present authors and co-workers, in which a novel Functional Model Based Method (FMBM) was postulated and applied for damage diagnosis on a laboratory aircraft skeleton structure [20]. The method is founded on the innovative class of data-based Functional Models (FMs), appropriate data pooling techniques, and proper estimation procedures (FMs were initially introduced by the last two authors in [21]; in [22] they were employed for damage magnitude estimation, and in [23] for damage detection under varying environmental conditions). This method allows for damage localization (in addition to detection and magnitude estimation) on 1D structural elements, that is elements with a single significant dimension. Even under this constraint, the damaged structural element must be first determined (a task relying on statistical hypothesis testing procedures), and, subsequently, a dedicated Functional Model – specific to the determined structural element – must be employed for precise localization [20]. Thus, beyond being limited to 1D structural elements, the method also becomes awkward and cumbersome for structures consisting of several elements, as both decision making mechanisms and several individual FMs are required.

The *aim* of the present study is the postulation and experimental assessment of a generalized data-based damage precise localization method overcoming the above mentioned limitations. The method should be thus capable of damage precise localization *anywhere* on *any* structure, consisting of *any* number elements, which are *not only* 1D, but (potentially) 2D and 3D as well, *without* the intermediate need for prior damaged element determination. This is to be achieved via a proper generalization of the FMBM, in which a *single* FM is used for the whole structural topology – not one per structural element. Moreover, the Generalized FMBM is set up to account for 2D and 3D structural elements via an expanded Vector-dependent FP-ARX (VFP-ARX) form allowing for three-dimensional operating parameter vectors (see Section 2; some initial developments on the method are presented in the conference paper [24]). In the inspection phase localization is achieved by estimating the current operating parameter vector within the single VFP-ARX model structure. Yet, the elements of the operating parameter vector are properly constrained, either via simple boundary constraints corresponding to the boundaries of 3D structural topologies or other suitable constraints corresponding to lower dimensional (1D or 2D) topologies. The (non-linear) estimation of the operating parameter vector is confined within the bounds of the specific structural topology, hence a damage is necessarily estimated *within* the topology – not outside it. An additional benefit stemming from this procedure is that the uncertainty bounds (in general uncertainty ellipsoids) associated with the estimated damage location are – by their own construction – restricted to the structural topology and of statistically optimal accuracy.

The effectiveness of the postulated method is demonstrated via damage precise localization on a relatively complex spatial laboratory structure consisting of 26 1D elements (rods) which are connected at 16 nodes via 74 bolts. A single damage corresponds to the loosening of any one bolt; each damage being characterized by its own Cartesian coordinates. Damage detection and – primarily – localization are investigated based on a *single* vibration acceleration response sensor – alongside a force excitation sensor. Anticipating the potential use of the method under natural (or otherwise limited) excitation conditions, the signals are measured within a very low and narrow bandwidth constrained to the 3–59 Hz range. The use of limited information is highly interesting and renders the problem more difficult, but also practical and realistic.

The rest of the article is organized as follows: The damage detection and precise localization method is presented in Section 2. The experimental set-up with the truss structure and the damage scenarios are presented in Section 3. The experimental results are presented in Section 4, and the conclusions are finally summarized in Section 5.