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A multi-stage approach for damage detection in structural systems based on flexibility

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ABSTRACT

The paper proposes a fusion approach for damage detection in structural applications in the case of multiple damage locations and three-dimensional systems. Based on the Dempster–Shafer evidence theory, a multi-stage approach is proposed with the mode shapes assumed as primary sources and local decisions based on a flexibility method. The proposed approach has been applied to two case studies, a a fixed end beam analyzed in other papers and a three dimensional structures codified in a Benchmark problem. Both the case studies have shown the ability and the efficiency of the proposed approach to detect damage also in the case of multiple damage, limited number of identified parameters and noise measurements.

1. Introduction

Damage detection in civil structures and infrastructures, such as buildings and bridges, still represents one of the main challenges that engineers face today. One of the main reasons relies on the fact that the instrumentation setup is generally limited in the case of civil constructions due to their extended dimensions and the necessity of containing operational costs. Thus far, although the scientific literature has proposed numerous damage detection methodologies, there is still a difficult to determine the position of damage in practice especially in the case of multiple locations where the results from different methods may not be in good agreement and are, sometime, discordant.

In recent years there has been an increasing interest of some researchers in methods, which fuse structural damage identification results from multiple sources. These methods all refer to information fusion techniques, which combine data from several information sources and achieve improved accuracies and more reliable results. Information fusion techniques have been widely used in many fields, such as in the defense system, robotics and intelligent vehicles, medicine and industrial engineering, etc., and only more recently they have been also applied in the field of detection of structural damage. Of interest is the work by Guo, 2006 [1] who proposed a structural damage detection using an information fusion technique applied to two sources, one based on frequency data and the other on mode shape data. The local decisions were obtained by the multiple damage location assurance criteria (MDLAC) and the frequency change damage detection method (FCDDM), respectively. The paper showed that with reference to a two-dimensional truss the results of the fusion approach were better than those obtained by the single methods especially in the case of multiple damage locations where the single methods generally failed. The results provided accurate estimation of damage locations also in the presence of measurement

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List of symbols

n	number of degree of freedom of the system
ϕ_i	ith mass-normalized mode shape of the undamaged system
ϕ_i^d	ith mass-normalized mode shape of the damaged system
ω_i	ith frequency of vibration of the undamaged system
$\boldsymbol{F}$	global flexibility matrix of the undamaged system
$\boldsymbol{N}$	number of elements composing the system
el_i	ith element composing the system
$\mathbf{F_{el_i}}$	local flexibility matrix related to a single element el_i of the undamaged system
$\mathbf{F^d_{el_i}}$	local flexibility matrix related to a single element el_i of the damaged system
$\mathbf{L_{el_i}}$	Boolean disassembly matrix relating global and elemental displacements
$\mathbf{S_{el_i}}$	matrix relating strain and elemental displacements
RDI_i	relative damage indicator at the single element el_i
θ	finite set of mutually exclusive hypothesis
2^θ	power set
S	subset of 2^θ
$m(S)$	BPA corresponding to S
S_1, S_2	information sources
$m_1(S_1), m_2(S_2)$	BPA corresponding to the source S_1, S_2
$m_1\left(\overline{S}_1\right)$	fused BPA through the Dempster's rule associated to the source $\overline{S}_1$
S_h	information source constituting by n_{S_h} couples of mode shapes
n_{S_h}	number of mode shapes constituting the information source S_h, $(n_{S_h} \in [1, \ldots, \overline{n}]$ with $\overline{n} \le n)$
$\overline{\phi}_j = \left(\phi_j, \phi_j^d\right)$	couples of mode shapes constituting the information source S_h
$\mathrm{RDI}_i^{[S_h]}$	relative damage indicator at the single element el_i for the source S_h
$\mathbf{F^{[S_h]}_{el_i}}$	local flexibility matrix of the element el_i for the source S_h (undamaged system)
$\mathbf{F^{[S_h],\,d}_{el_i}}$	local flexibility matrix of the element el_i for the source S_h (damaged system)
$\mathbf{F^{[S_h]}}$	flexibility matrix for the source S_h (undamaged system)
$F^{[S_h],\,d}$	flexibility matrix for the source S_h (damaged system)
$m_h(S_h)$	BPA corresponding to the source S_h (local decision)
$m_{j+1}\left(\overline{S}_{j+1}\right)$	vector of the fused BPA through the Dempster's rule for the source $\overline{S}_{j+1}$
$m_{n-1}\left(\overline{S}_{n-1}\right)$	vector of fused BPA through the Dempster's rule (last stage procedure)
$Bel(Y)$	belief for the subset Y
$\mathbf{M}$	nxn mass matrix of the system
$\mathbf{I}$	nx1 identity vector
M_{tot}	total mass of the system
Γ_i	ith modal participation factor
M_i^*	ith participation mass ratio

errors. In Guo and Zang, 2006 [2] the authors extended the fusion approach to a weighted balance evidence theory (WBET) where some weighted coefficients were applied to the single sources in order to differentiate their importance and reliability. The method has been applied to the two-dimensional truss analyzed in the other paper [1] and has been shown also more effective than the single methods and the basic evidence theory, although it poses the problem of how to define the different coefficients to be applied. Guo and Li, 2009 [3] proposed a two-stage method consisting, at first, of a fusion damage approach applied to frequency and mode shapes data to detect the damage locations and, next, of a micro-search genetic algorithm (MSGA) applied to evaluate the damage extent. The method is applied to a cantilever beam and it has been shown to be effective also because it reduces the space size where the optimal solution is searched by the MSGA. The efficiency of the method has been also examined in the presence of measurement noise. In Guo and Li, 2011 [4] the two-stage approach of the previous paper has been modified in two main aspects. First, the fusion has been applied to the frequency change identification method (FCI) and the modal strain energy dissipation ratio (MSEDR). Then the damage quantification has been obtained by using an energy balance equation (EBE) index. The efficacy of the method has been shown with reference to a two-dimensional and a three-dimensional truss structures also in case of measurement noise. Bao and Li, 2007 [5] and Li et al, 2008 [6] proposed to apply the evidence theory to different artificial neural network (ANN) with different weighted coefficients. The method has been applied to the numerical study of the Binzhou Yellow River Highway Bridge and has been shown more effective than the single ANN also in presence of noise. Fei et al., 2009 [7] proposed a cumulative information fusion technique applied to the modal strain energy ratio (MSECR) by using the mode shapes of different orders as information sources. The efficiency of the method has been tested with reference to a fixed end beams in the single and multiple damage cases. Jiang et al., 2011 [8,9] proposed a two-stage structural damage detection method based on the integration of fuzzy neural network and data fusion. The method has been proposed for cases where the measurement data was very large and with uncertainties and it was applied to a numerical simulation of a 7-degree of freedom building model.

The results of the previous papers show that the data fusion is certainly well appropriate in improving the efficiency of the damage detection process. However, there are some issues to be further investigated. One of the most important is that related to analyze more specifically three-dimensional structural systems with their related aspects among which the effect of limited number of identified parameters, which is a very common feature of the civil constructions field.

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