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Shaped input distributions for structural damage localization

Martin D. Ulriksen [a,*], Dionisio Bernal [b], Lars Damkilde [a]

[a] Department of Civil Engineering, Aalborg University, 6700 Esbjerg, Denmark
[b] Civil and Environmental Engineering, Center for Digital Signal Processing, Northeastern University, Boston, MA 02115, United States

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ABSTRACT

Given a structure in a state with any type of perturbation, the steady-state vibrational response will be identical to that in the unperturbed state if the perturbation is rendered dormant and, of course, if the load distribution is the same in the two states. Guided by this principle, a damage localization method is cast that operates on the premise of shaping inputs—whose spatial distribution is fixed—by use of a model, such that these inputs, in one structural subdomain at a time, suppress certain steady-state vibration quantities (depending on the type of damage one seeks to interrogate for). Accordingly, damage is localized when the vibration signature induced by the shaped inputs in the damaged state corresponds to that in the reference state, hereby implying that the approach does not point directly to damage. Instead, it operates with interrogation based on postulated damage patterns, resulting in a system identification-free procedure whose primary merits, besides avoiding the typical bottleneck of system identification, include a low demand on output sensors, robustness towards noise, and conceptual simplicity. The price paid for these merits is reliance on a relatively accurate model of the structure in its reference state and the need for multiple controllable inputs.

1. Introduction

A conventional strategy for circumventing conditioning difficulties associated with damage characterization is to factor the problem into detection, localization, and quantification [1]. While damage detection has been resolved with reasonable success using unsupervised learning algorithms adapted from the fields of pattern classification and machine learning, see, for example, [2–5], a robust solution to the central piece of the triad, the localization component, has proved difficult. Information on the location of structural damage is useful in cases where deterioration, despite having been detected, is troublesome to find because of its size, or if the part of the structural domain to be visually inspected is large and/or contains critical areas that are hidden from view. As an example to the latter, one can think of wind turbines in which many areas likely to experience structural deterioration are located within the blade surfaces, making them difficult—and sometimes even impossible—to reach for human inspection [6]. This inaccessibility combined with the high costs typically associated with visual inspections motivate work on damage localization procedures.

Vibration-based damage localization methods are traditionally cast with the aim of finding damage-induced differences between vibration signatures from the structure in its healthy/reference state and its damaged one. The damage-induced differences, which, for instance, could be mode shape changes or shifts in the transfer functions, are then mapped to the

* Corresponding author.
E-mail address: mdu@civil.aau.dk (M.D. Ulriksen).

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structural domain; either directly or by use of a model of the structure. The direct approaches are denoted data-driven and examples can be found in [7], while the approaches implementing a model, including the damage locating vector (DLV) schemes proposed by Bernal [8–11], are referred to as model-based [12,13].

The dynamic damage locating vector (DDLV) method [10] and its stochastic counterpart, the SDDLV method [11], rest on a theorem stating that the span of the null space of the damage-induced change in the transfer matrix contains vectors that are Laplace transforms of dynamic excitations inducing zero stress over the damaged subdomain. In these methods, the model errors affect the mapping of the experimental feature to the structural domain, but what typically limits robustness is the difficulty in extracting the experimental feature with adequate accuracy in the required system identification. In this paper, an alternative is explored where the excitations used to locate the damage are formulated from the model and then applied to the actual structure, hence lowering the accuracy needed on the experimental component. While model error may play a more important role in the proposed scheme than in the DDLV and SDDLV methods, the most important price paid for the change in the experimental feature is the need for multiple controllable inputs and the fact that the scheme to be described does not provide results that "point to the damage". Instead, it is restricted to answering, for a set of postulated damage distributions, which is more likely to correspond to the physical situation. For convenience in the subsequent discussion, we shall refer to the approach to be outlined (wherein the damage locating loads are obtained from a model) as the shaped damage locating input distribution (SDLID) method.

Among the positive features of the SDLID method is, as shall be apparent after the theory is discussed, the low demand on the number of output sensors and conceptual simplicity. The low demand on output sensors is an attractive feature, which is typically only achieved when using local guided waves-based approaches [14,15]. An issue that can limit the applicability of the SDLID scheme is the required number of actuators. This number can vary drastically depending on the structural topology and on whether it is necessary to consider multiple damage locations. The general principle is that the number of actuators must be larger than the number of deformation modes that must be controlled to realize a stress field that is zero over the desired part of the domain.[1] In the case of truss structures with stiffness damage, the number of actuators must be higher than the number of damaged bars, but in the case of a continuum, the number of required actuators is theoretically infinite, as it is otherwise impossible to produce identically zero stress over any finite-sized closed region. Needless to say, useful results in the continuum can be expected once the number of actuators is above some value; although it is clear that practicality requires that this number is small, except, perhaps, in the case of small piezo-electric actuators such as those used by Bernal and Kunwar in [16].

The present paper describes the theory of the SDLID scheme and includes a numerical section, where two academic examples are used to gain some indication on the type of performance that may be expected in cases where the SDLID scheme can be considered applicable. Specifically, we consider a plane-stress problem with a rectangular domain and a relatively large truss structure model, which both are introduced to a crack that is modeled in a smeared manner by reducing the stiffness of a certain region. Albeit simplistically, we account for inevitable model discrepancy, for noise in the measurements, and for the fact that, in addition to the shaped inputs, there may be other excitations that contaminate the response.

2. Input shaping for vibration suppression

Consider an undamaged structural domain that is discretized with n degrees of freedom (DOF) and subjected to $p \leqslant n$ controllable inputs, which act in the DOF indexed by $\mathcal{T} = \{\mathcal{T}_1, \mathcal{T}_2, \ldots, \mathcal{T}_p\} \subseteq \mathcal{Q}$, with $\mathcal{Q} = \{1, 2, \ldots, n\}$. Under the assumptions of linearity and time-invariance, the temporal equilibrium equation is

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t), \tag{1}$$

where $K, C, M \in \mathbb{R}^{n\times n}$ are the stiffness, damping, and mass matrices, $f(t) \in \mathbb{R}^n$ is the nodal load vector, and $x(t),\ \dot{x}(t),\ \ddot{x}(t) \in \mathbb{R}^n$ are the nodal displacement, velocity, and acceleration vectors.

The basic idea of input shaping is to apply a set of controllable inputs, $f_{\mathcal{T}}(t)$, that render certain vibration quantities dormant in a subdomain of the structure [17,18]. In practice, the nature of the inputs will, of course, be governed by the available actuators, but also, in some cases, potentially by other deterministic loads that might affect the structure in question. One can, for example, think of situations with rotating equipment where a harmonic load is fixed (both spatially and temporally) such that $p - 1$ inputs can be shaped accordingly. In Sections 2.1 and 2.2, two different approaches for extracting the shaped input distribution, where each has merit for particular input types, are outlined.

2.1. Laplace domain approach

Assuming steady-state and/or zero initial conditions, the output from Eq. (1), with the p controllable inputs acting solely in the DOF indexed by $\mathcal{T}$, can be expressed in the Laplace domain as

$$x(s) = (Ms^2 + Cs + K)^{-1} f(s) = G(s)f(s) = G_{\bullet,\mathcal{T}}(s)f_{\mathcal{T}}(s), \tag{2}$$

[1] This requirement on the number of actuators is for the theory to hold exactly but not necessarily for the approach to be able to provide useful results.