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# Hybrid computational strategy for structural damage detection with short-term monitoring data

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ABSTRACT

The scenario of damage detection of a structure without permanent structural health monitoring system is explored. Dynamic responses are collected from different measurement setups and excitations in different regions of a structure. All the measured data are analyzed together in the proposed strategy with consideration of the different excitations. Local damages in terms of physical structural parameters are evaluated from the direct analysis using the Pattern Search method with a hybrid parallel computing strategy using CPU and GPU instead of the usual inverse analysis. The objective function is the difference between the measured and calculated responses from an updated finite element model of the structure. The proposed approach is illustrated with a plane frame structure with different tests and measurements in three regions. The effect of the size of the Generating Matrix of the Pattern Search method is also investigated and discussed. There is noted and improved computation efficiency when a large Generating Matrix with 2000 columns is used. The simulations illustrate the feasibility of using a few sensors for the damage detection of a large-scale structure with short-term monitoring data.



## 1. Introduction

In full-scale health monitoring of a structure, many situations exist where measurements from tests conducted in different parts of the structure are required. This is particularly true for structures with no permanent monitoring sensors installed. The test and measurements are usually referred to as the "short-term monitoring" mobilizing sensors in different parts of the structure. Different excitations of the structure in different tests have to be taken into account. The obtained measurements are influenced by the statistical uncertainty due to measurement noise, nonstationary and colored excitation noise, and many other sources. The change in modal properties across major loading events has been explored for structural health monitoring [1,2]. However, nothing has been done to merge the corresponding data for damage detection while taking into account possible different excitations between the measurements as if there was a large number of sensors.

Many estimation methods have been proposed for a structure with unknown input [3–8] to meet the different practical needs in field measurement. Li and Chen [4] proposed a statistical algorithm to estimate the structural parameters and the input information. Lu and Law [5] proposed a two-stage sensitivity-based method to identify the structural parameters and excitation force. Other methods based on Quadratic Sum-Squares Error [6], Sequential nonlinear least-square estimation [7],

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Extended Kalman Filter [8], etc. were also reported. All of them, however, require the solution of a non-linear least-squares problem with regularization or singular value decomposition [9–11]. It is mathematically demanding with also the need of an analytical model. Other popular pattern matching methods, such as the Neural Networks, Genetic algorithm [12–13] and the Pattern Search method [14,15] have also been proposed. Zhang [14] made use the Pattern Search method for model selection in a nonlinear system. Kourehli [15] also used the Pattern Search method for damage detection with incomplete modal data. The direct search method is characterized with no requirement on the information of derivative, and it is the best choice for the solution when the objective function is nonlinear, discontinuous or non-differentiable, or the derivative information is not reliable. They also have the advantages of flexibility, robustness, and simplicity in finding the solution. It has also been reported that the Pattern Search methods can be more robust to local minima than the derivative-based methods [16].

This paper addresses the analysis of data collected from multiple measurement setups of an existing structure from short-term monitoring. Different zones of the structure with independent sensor and excitation configurations according to its finite element configuration of convenience are independently test. The external excitations in each test are estimated in the wavelet domain from the collected dynamic responses with a conventional inverse analysis. The structural damage detection of the whole structure is realized with the Pattern Search method instead of an inverse analysis technique to illustrate the simple and rapid computation with parallel computing making simultaneous use of all sets of measurement from the structure. Both the identified external excitations and the local damages can be further improved with more iterations of model updating. Simulation results with a plane frame structure show that this approach of parallel computing with a large Generating Matrix could achieve a reduction of approximately 34% computation effort but with similar accuracy compared to results from computation using a single CPU.

## 2. Force identification

### 2.1. The equation of motion

The equation of motion of a $N$-degrees-of-freedom (DOFs) linear damped structural system under external excitation can be written as

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=\boldsymbol{B}\boldsymbol{f}(t) \tag{1}$$

where $\boldsymbol{x}$, $\dot{\boldsymbol{x}}$ and $\ddot{\boldsymbol{x}}$ are vectors of displacements, velocity and acceleration responses of the structure, respectively; $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the mass, damping, and stiffness matrices of the structure, respectively. Rayleigh damping is assumed which is of the form $\boldsymbol{C}=a_1\boldsymbol{M}+a_2\boldsymbol{K}$, where $a_1$ and $a_2$ are damping coefficients to be determined from the first two modal damping ratios. $\boldsymbol{f}(t)$ is the external excitation force vector, and $\boldsymbol{B}$ is the location matrix associated with vector $\boldsymbol{f}(t)$. The mass matrix of a structure can be accurately estimated based on its geometry and material information and is assumed invariant. The dynamic responses of the structure can thus be obtained from Eq. (1) using a step-by-step integration method [17].

### 2.2. Unit impulse response function in wavelet domain

The unit impulse response (UIR) is the response function of the system under the input of a unit pulse at a specific location, and it is an intrinsic function of the structural system. The UIR function with the force vector applied at a specific DOF has been derived analytically from the equation of motion [18] of the system and it will be briefly introduced below.

The equation of motion in Eq. (1) can be re-written as follows when under the unit impulse excitation as

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{C}\dot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=\boldsymbol{B}\delta(t) \tag{2}$$

where $\delta(t)$ is the Dirac delta function. The impulse response function can be represented as a free vibration state with some specific initial conditions. Assuming that the system is in static equilibrium initially, the UIR function can be computed from Eq. (3) as

$$\begin{cases} \boldsymbol{M}\ddot{\boldsymbol{h}}(t)+\boldsymbol{C}\dot{\boldsymbol{h}}(t)+\boldsymbol{K}\boldsymbol{h}(t)=0 \\ \boldsymbol{h}(0),\ \ \dot{\boldsymbol{h}}(t)=\boldsymbol{M}^{-1}\boldsymbol{B} \end{cases} \tag{3}$$

where $\boldsymbol{h}(t)$, $\dot{\boldsymbol{h}}(t)$ and $\ddot{\boldsymbol{h}}(t)$ are the unit impulse displacement, velocity and acceleration vectors, respectively.

When the structural system is under general excitation $\boldsymbol{f}(t)$ with zero initial conditions, the acceleration response $\ddot{\boldsymbol{x}}_s(t_n)$ from sensor location $s$ at time instant $t_n$ is

$$\ddot{\boldsymbol{x}}_s(t_n)=\int_0^{t_n}\ddot{\boldsymbol{h}}_s(t_n-\tau)\boldsymbol{f}(\tau)d\tau \tag{4}$$

in which, the subscript $s$ denotes the quantity at sensor location $s$. Eq. (4) represents the input–output relationship of the dynamic structural system under the input force $\boldsymbol{f}(t)$ at a specific location. The vectors $\ddot{\boldsymbol{h}}_s(t_n-\tau)$ and $\boldsymbol{f}(\tau)$ can be expanded in