Vibration-based Damage Identification using the Multi-Particle Collision Algorithm with Hooke-Jeeves coupled with NASTRAN

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Abstract

The structural vibration-based damage identification is solved as an inverse problem. The problem is formulated as an optimization problem, minimizing an objective function of the least square error between the measured displacement and the displacement computed by the forward model. The minimization process is handled by the hybrid metaheuristic Multi-Particle Collision Algorithm with Hooke-Jeeves method. The methodology is tested over a truss structure modeled by the NASTRAN software. The inverse solution modifies the NASTRAN's input file and obtains the computed displacement in the time-domain from the NASTRAN output punch file. Experimental data was created *in silico*. Time-invariant damages were assumed to generate the synthetic displacement data.

Keywords: Vibration-based damage identification, hybrid metaheuristic algorithm, inverse problem.

1. Introduction

The Structural Health Monitoring (SHM) belongs to the field of System Identification. SHM performs a global damage identification in structures. The capacity of early identifying damages allows to repair or rehabilitate a structure before it failures [1].

Identifying damages in an accurate and a safe way is essential in critical systems, such as some civil, mechanical, and aerospace infrastructures.

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Damages which are not identified could produce catastrophic consequences, with human and economic losses.

The damage identification process attends four performance levels [2]: Detection, Location, Extension, and Prognosis. The first three levels are related to the damage diagnosis [3]. When the structures have a high number of degrees of freedom, the damage identification process becomes a computationally expensive task. It is necessary to develop a method that could solve the problem with a low number of objective function evaluations.

The development of complex engineering structures starts, usually, with the design of a computer model for the structure analysis. The design is aided by engineering software tools, known as Computer-Aided Engineering (CAE). NASTRAN (NASA Structural Analysis System) is a powerful general purpose finite element analysis package for use in the Computer-Aided Engineering process [4, 5].

Stochastic optimization has became an important tool to solve problems with nonlinear and multi-modal cost functions [6]. Stochastic methods use random processes to generate new solutions, combining the exploration in the search space with the exploitation processes.

Recently, a hybrid algorithm using the Multi-Particle Collision Algorithm in combination with the Hooke-Jeeves direct search method was used in the damage identification over some simple structures: a 10-DOF mass-spring-damper system, a beam, and a three-bay truss [7, 8]. The hybrid algorithm is described in the Section .

The objective of this work is to extend these results, improving the inverse solution substituting the structure models implemented in FORTRAN with the NASTRAN. The inverse solution using NASTRAN is briefly explained in the Section .

The method is applied in two case studies: a spring-mass system with 10-DOF (see Section), and a truss system with 8-DOF (see Section).

The next section presents the Vibration-based damage identification problem solved as an optimization problem.

2. Vibration-based damage identification problem as an optimization problem

2.1. Forward problem

The dynamic response of motion of a structure is given by a second order, non-homogeneous ordinary differential equation, shown in Eq. (1). In the equation, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ represent the $d \times d$ mass, damping and stiffness matrices, respectively; d is the number of degrees of freedom of the structure. Vector $\mathbf{F}$ represents the external forces, and vectors $\mathbf{u}$, $\dot{\mathbf{u}}$, $\ddot{\mathbf{u}}$ are the displacements, velocity and acceleration, respectively. The initial conditions for the model are given by Eq. (2) and Eq. (3).

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t)\,; \tag{1}$$

$$\mathbf{u}(0) = \mathbf{u}_0; \tag{2}$$

$$\dot{\mathbf{u}}(0) = \dot{\mathbf{u}}_0. \tag{3}$$

Solving the forward problem, with $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, and $\mathbf{F}$ known, we can obtain the system displacement $\mathbf{u}$.

A numerical solution for this model is obtained using the Newmark method since no analytical solution exists for any arbitrary functions of $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ and $\mathbf{F}$ [9].

2.1. Inverse problem

In this work, the inverse problem of localizing and quantifying damages on structures is solved as an optimization problem, in which we minimize the squared error between the computed displacement $\mathbf{u}_i^{mod}$ and the measured displacements $\mathbf{u}_i^{obs}$ of the structure, as presented in Eq. (4):

$$J(k) = \sum_{i=0}^{d_m} \left[\mathbf{u}_i^{obs}(t) - \mathbf{u}_i^{mod}(\mathbf{k}, t)\right]^2 \,, \tag{4}$$

where t represents the time, d_m is the number of measured displacements, and $\mathbf{k} = (k_1, k_2, ..., k_n)$ contains the values of the stiffness for each element (with n elements in total).

This inverse problem is to be solved using optimization algorithms, in this case, a hybrid method MPCA-HJ. The objective function values are calculated comparing the computed model response ($\mathbf{u}_i^{mod}$), after running the structural model with the assumed stiffness values, with the experimentally measured response acquired from the vibration experiments ($\mathbf{u}_i^{obs}$).

Figure 1 shows a representation of the inverse solution procedure.

3. Optimization algorithm: MPCA-HJ

3.1 Multi-Particle Collision Algorithm

The creation of PCA was inspired by the physics of nuclear particle collision reactions [10, 11]. In the nuclear reactor, some phenomena occur,

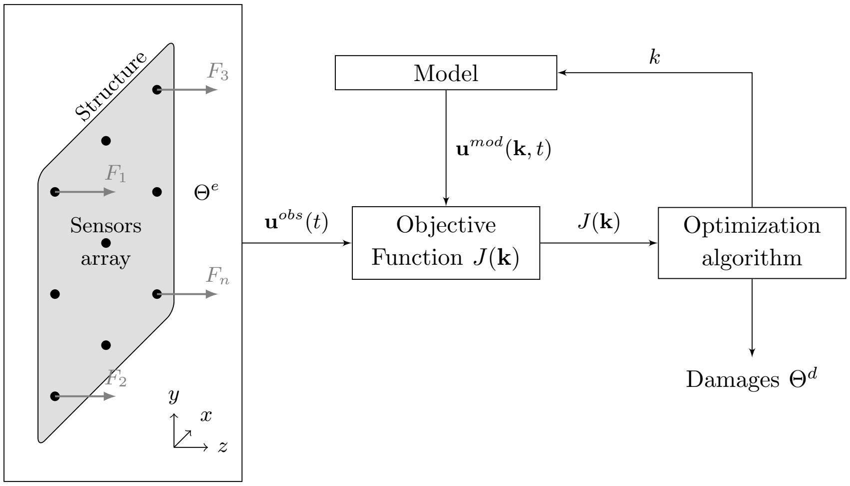

Figure 1 – Solution procedure of the Vibration-Based Damage Identification as optimization problem

including scattering (an incident particle is scattered by a target nucleus) and absorption (an incident particle is absorbed by the target nucleus), as shown in Figure 2.

MPCA can be loosely described as an algorithm consisting of a set of particles traveling inside a nuclear reactor. New particles are generated, and they can be absorbed or scattered, depending on their fitness, and if the fitness is better, they will substitute the *old* particles.

Figure 2 – Phenomena inspiring Multi-Particle Collision Algorithm

A parallel version of the MPCA was developed, taking advantages of a high-performance environment. A flowchart is shown in Figure 3. In each processor (of a total of $N_{processors}$), $N_{particles}$ candidate solutions are set. This partition leads to a considerable reduction of computing time [12].

MPCA starts with initial particles randomly created spread all across the search space. After creating the initial set, a blackboard strategy is used for sharing the best particle among all the particles. Later, the particles traveling process is started, involving three main functions: Perturbation, Exploitation, and Scattering [12, 10].

Particles in the whole population behave cooperatively, i.e., in the ending of each main loop, if a number of function evaluations ($N_{blackboard}$) was reached after the last blackboard updating, the best particle overall is shared for all other particles in the set, through a blackboard strategy.

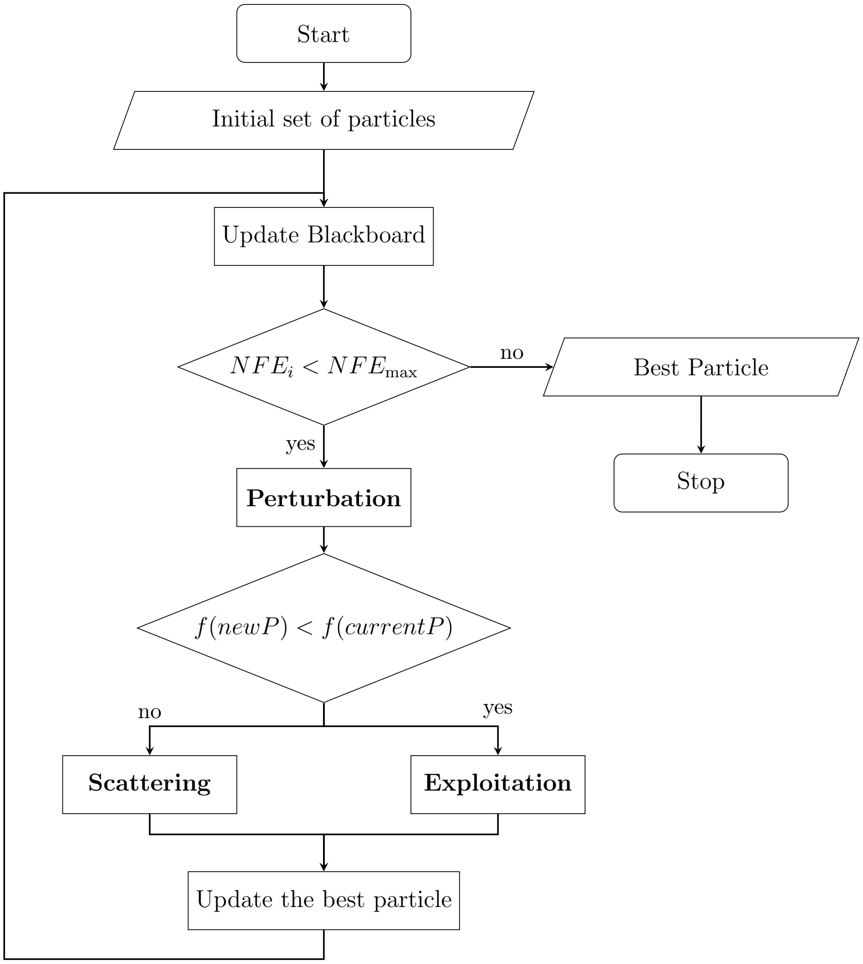

Figure 3 – Multi-Particle Collision Algorithm

For stopping criterion, a maximum number of function evaluations ($NFE_{\max}$) is defined.

The current version MPCA was implemented in FORTRAN 90, using OpenMPI libraries.

3.2. Hooke-Jeeves Direct Search Method

The direct search method of Hooke-Jeeves (HJ) [13] consists of the repeated application of exploratory moves about a base point which, if successful, is followed by pattern moves. Details about the algorithm of HJ can be found in the literature [13].

4. Solving the inverse problem using NASTRAN

The proposed damage identification approach takes the NASTRAN as the simulator of the structural model, and the hybrid metaheuristic MPCA-HJ as the optimizer.

The main program modifies the NASTRAN input file. The stiffness values must be written in the appropriate element position with the correct format. Then the `nastran` application is called, to simulate the performance of the structure with the stiffness values configurated. The NASTRAN return the requested data (such as displacement, frequency response, modal data) written in a punch file (.PCH). In the next step, the program takes the obtained data (computed model response $\mathbf{u}_i^{mod}(\mathbf{k}, t)$) and compares them with the experimentally measured response ($\mathbf{u}_i^{obs}(t)$).

5. Case Studies

5.1. Spring-mass system with 10-DOF

A spring-mass system with 10-DOF, as shown in Figure 4, is tested. In this case, $k_{1-9} = 100N/m$, $k_{10} = 1000N/m$, $m_{1-9} = 0.1kg$ and $m_{10} = 10kg$, and the system is excited with a external force $P = 200N$ applied over the element m_2.

In the spring case, the NASTRAN card to be manipulated is the CELAS2. Each line represents a single element. The third column in the card represents the stiffness of the scalar spring, as shown as follow:

```
$ 1-----2-------3-------4-------5-------6-------7-------8-------
CELAS2  11      100     1       2       2       2
```

Figure 5 shows the results of the damage identification with noiseless data graphically. Each separation in the graph box represents an element in the structure; the blue bar represents the value of the damage to be estimated, and the red bar the damage identified. In this case, results are almost perfect.

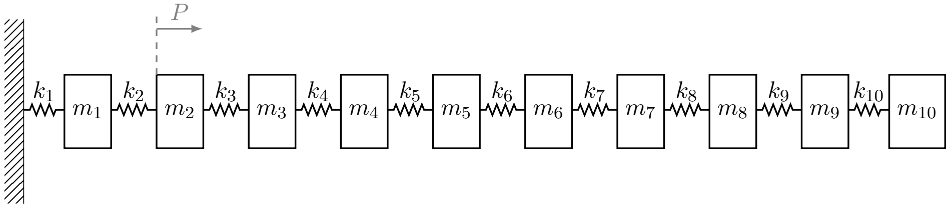

Figure 4 – Spring mass system with 10-DOF

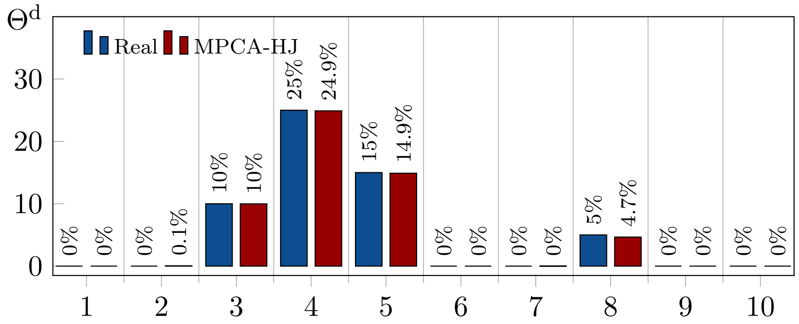

Figure 5 – Damage identification on the spring-mass system

5.2. Cantilever Truss

The other case study is the Cantilever Truss [14], a truss system composed of 10 bars, as shown in Figure 6. The structure configuration was taken from the NASTRAN Compatible Finite Elements (CoFE)[2] [15]. In this case, $L = 9.144m$, $P = 444.82kN$, Young's modulus equal to $6.895 \times 10^{10}Pa$, and a specific mass equal to $27679,9kg/m^3$, with a minimum area of $0,00064516m^2$.

In the case of the truss system, the NASTRAN card to be manipulated is the MAT1, which represents the material of a single element, in this case a bar. Each line in Figure 6 represents a single bar. The third column in the card represents the Youngs modulus, and this is the value modified in this case for representing the losses of stiffness:

```
$ 1-----2-------3-------4-------5-------6-------7-------8-------
MAT1    101     1.E7            .33     2.59E-4
```

Figure 7 shows the results of the damage identification with noiseless data graphically. Again, each separation in the graph box represents an

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[2] http://vtpasquale.github.io/NASTRAN_CoFE/tenBarTrussOptimization.html

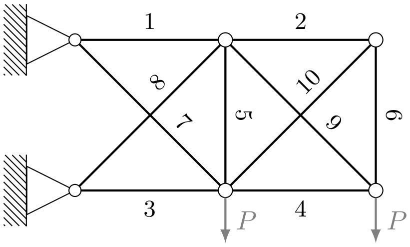

Figure 6 – Two-bay truss structure

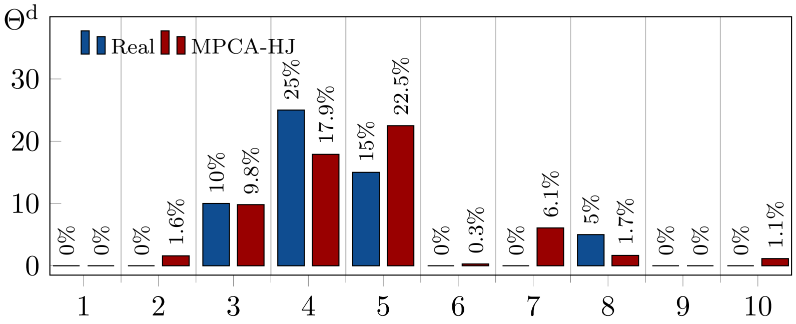

Figure 7 – Damage identification on the truss structure

element in the structure; the blue bar represents the value of the damage to be estimated, and the red bar the damage identified. In this case, results are worst than in the spring-mass system. The damages in the 3^{rd}, 4^{th} and 5^{th} elements were identified, but the method fails to estimate the damage severity. The damage located at the 8^{th} element was not correctly estimated, and in the 7^{th} element a false alarm appeared.

Final Remarks.

The inverse problem of structural damage identification was solved using the hybrid method MPCA-HJ coupled with NASTRAN.

For the spring-mass system, the results were almost perfect, while for the truss structure some differences from the real damage values were verified. A small damage was not properly identified, while a false alarm appeared for the element that crosses with that damaged element.

In further works, other variants of the MPCA-HJ and other metaheuristic algorithms will be applied. Also, more complex structures will be modeled in NASTRAN, such as International Space Station [16]. Some numerical experiments will also be performed using incomplete experimental data for simulating real conditions.

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