Structural Damage Identification: Parallel - Hybrid - Hierarchical Approach

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Abstract. *A hybrid technique for estimation of structural damage, using variational method (VM) and genetic algorithm (GA), was proposed in Chiwiacowsky, 2005. In Sambatti, 2004 was analyzed and compared some ways of parallelization of a genetic algorithm (PGA). The project here presented aims to using the PGA to start the VM, and doing a hierarchical search for structural damage: parallel - hibrid - hierarchical aprroach.*

Until to find an homogeneous region the idea is to make the division of the structure (aircraft, for example) within the original divisions. The latest step was the successive division of the homogeneous region like the dynamic growth of a tree (breadth-first): with probabilistic branching - occurring if and only if there was some damage on the node in question.

Initial results indicates that, in case of random distribution of damage, the best tree is the binary type, presenting a linear behavior of the cost (algorithm's complexity) against the number of items in the structure - showing the robustness of the methodology when applied to large structures. On a structure of a million of elements, with density of random damage of one percent, the hierarchical search takes only forty percent of the computing time agreed to the classical (exhaustive) search to provide the same results on an academic test.

1. Introduction

The mathematical modeling of dynamic processes in mechanical vibration is characterized by the measurement of displacements, accelerations, deformations, stresses, natural frequencies and modes of vibration, since known initial conditions, geometric configuration of the structure and the properties of it's material. In these cases, the problem is identified as the direct problem.

The inverse problem appears when the responses from a mechanical system are known - have been obtained experimentally - and the goal is the determination of the characteristics listed at the preceding paragraph: initial conditions, geometric configuration and properties of material [1].

Since the values of properties, such as damping and stiffness, are known when the manufacture of an aircraft, the comparison between these data and new measurements is one of possible ways to assess structural damage. However, these new measurements are

not necessarily direct measurements, but also results of inverse problems, as the previously presented.

The use of global techniques for identification of damage, based on the response characteristics of the structure, is based on the fact of the presence of a fault changing the structural properties of the system, which in turn lead a change in its dynamic response, which may be assessed by measures in the time domain, frequency domain or in the modal.

To solve this inverse problem will be used on this research methods from the Calculus of Variations (Functional Analysis) and Artificial Intelligence, the first source provide the Conjugate Gradient Method (CGM), and the second the Genetic Algorithms (GA).

In Chiwiacowsky, 2005 [2] has already implemented the GCM (MV) in the form of adjoint equation (Lagrange Multiplier - LM), been initialized by a GA (not parallel) in order to solve the inverse problem here discussed; and in Sambatti, 2004 [3] was presented a parallel implementation of a GA (PGA). The central objective of this research is to significantly increase the speed of identification of damage, using the products and methodologies of these previous works, attacking the problem at two levels:

(i) initialization of the method: using the PGA to provide the initial condition of the CGM-LM.
(ii) a search strategy: applying an hierarchical approach to evaluating the different areas where damage may be present, starting with a coarse discretization and promoting gradual refinement only in areas with possibility of damage was not discarded yet.

It is hoped that with such upgrade, the methodology becomes robust sufficient for the identification of structural damage in real structures of thousands (even millions) of degrees of freedom.

This article is well organized: In the section Previous Works is discussed the use of GA to initialize CGM, and the parallel GA. Then the methodology is presented (what is the hierarchical approach, and how the artificial damage was generated), and is shown the first results. Finally we discuss the conclusions and perspectives of the research.

2. Previous Works

2.1. Using GA to initialize CGM

Methods based on gradient use not only the information of the objective function (direct search), but also of its derivate, usually converging faster than direct search methods. The use of conjugated directions for the search collaborates even more to accelerate the rate of convergence.

The method adopted in this research is based on the Alifanov variational approach [4] [5]. The method of Alifanov as originally formulated does not produce a satisfactory inverse solution, especially because in hyperbolic problems, such as mechanical vibrations, inaccuracies in initial conditions are not eliminated over time, what occurs in parabolic problems, such as transmission of heat; being developed (Chiwiacowsky, 2005)

[2] a hybrid strategy, where the initial estimate for the conjugate gradient method to the formulation of Alifanv is obtained by a genetic algorithm.

The hybrid technique has been used in problems of discrete structural damage (frames) and continuous (beams) [10] and in a problem of space technology (detection of damage in International Space Station [11]). In all cases mentioned the technique showed very good results [6] [7] [8] Leo-2008b.

In figure 1 an ilustrative diagram of the conjugated gradient method.

Step 1: Choose an initial guess $\mathbf{K}^0$.
Step 2: Solve the direct problem, Eqs. (1)–(2), to obtain $\mathbf{x}(t)$.
Step 3: Solve the adjoint problem, Eqs. (15)–(16), to obtain the *Lagrange* multiplier vector $\lambda(t)$.
Step 4: Knowing $\lambda(t)$, compute the gradient function vector $\mathbf{J}'[\mathbf{K}]$ from Eq. (19).
Step 5: Compute the conjugate coefficient vector γ^n from Eq. (22).
Step 6: Compute the direction of descent vector $\mathbf{P}^n$ from Eq. (21).
Step 7: Set $\Delta\mathbf{K} = \mathbf{P}^n$ [14], and solve the sensitivity problem, Eqs. (10)–(11), to obtain $\Delta\mathbf{x}(t)$.
Step 8: Compute the step size vector β^n from Eq. (24).
Step 9: Compute $\mathbf{K}^{n+1}$ from Eq. (20).
Step 10: Test if the stopping criteria, Eq. (28), is satisfied. If not, go to step 2.

Figure 1. Ilustrative diagram of the conjugated gradient method. SOURCE: Chiwiacowsky, 2005 [2]

2.2. Parallel GA

One of the most important aspects of the genetic algorithm is its ability to paralellization. Currently, genetic algorithms have been widely applied, but parallel implementations are recent [3].

Each processor performs a GA on its own population and migration of individuals with better fitness occurs regularly between processors. An epidemic operator was proposed to remove a large percentage of individuals in a population where there is no improvement in fitness, so a new population is generated and only those with better skills are preserved.

The parallel genetic algorithm (PGA) is the replication of the tasks of a simple genetic algorithm for different processors, and the basic idea is that each processor can create new individuals and calculate their skills in parallel.

In figure 2 an ilustrative diagram of the parallel genetic algorithm.

3. Methodology

The initial tests have been performed to verify the feasibility of the objectives (i) and (ii) of the research. For (i) will soon implement the PGA to initialize the CGM-LM and

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Parallel_Genetic_Algorithm
 Define and initialize the evolutionary parameters;
 t ← 0;
 Generate a random population Pop(t);
 Calculate the fitness J(f_ξ) of each individual in Pop(t);
 While (condition)
      t ← t + 1;
      Select a pair of parents (X_1, X_2) from Pop(t − 1);
      Cross over the pair (X_1, X_2);
      Mutate the new string X generated;
      Insert the individual X in the worst location of Pop(t − 1);
      Calculate the fitness of the individual X;
      X*(t) ← Best[Pop(t)];
      If (migration) then
           X_migrante ← X*(t)
           Send individual X_migrante to the other processors;
           X_recv ← recv_idivduo(X_migrante);
           X_delete ← Worst[Pop(t)];
           Replace X_delete by X_recv;
      End_If
      If (X*(t) = X*(t − 1)) then
           cont_epidemic ← cont_epidemic + 1;
           If (cont_epidemic > limit) then
                Apply Epidemical on Pop(t);
           End_If
      End_If
 End_While
 End
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Figure 2. Ilustrative diagram of the parallel genetic algorithm. SOURCE: Sambatti, 2004 [3]

comparing the results of inversion with this method with those found with non-parallel version of GA. Comparing effectiveness and efficiency. For (ii) the test was done on a homogeneous plate, taking data without noise.

In practice before to find a homogeneous region the idea is to make the division of the structure (like an aircraft) within the divisions originating(Figure 3).

First level of division:
- Left-wing,
- Right-wing,
- Body of the aircraft (the largest drum) divided into 3 parts (front, middle (region of crimping of the wings), rear)
- Main rudder and lower wings (the whole).

In the example, the damage was detected at the end of the aircraft. The structure is re-divided into:
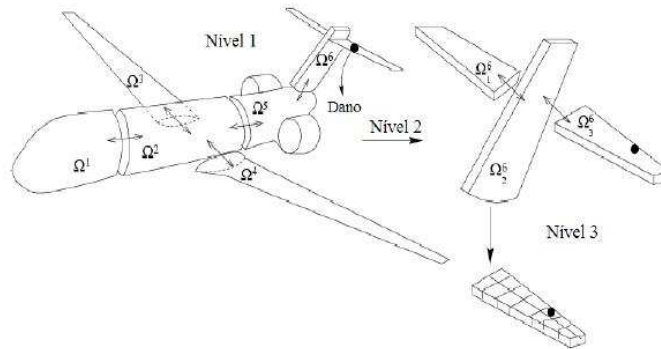
Figure 3. Aircraft division. SOURCE: Chiwiacowsky, 2005 [2]

- Left-wing,
- Right-wing,
- Body of the aircraft (the larger cylinder) divided into 3 parts (front, middle (crimping of the wings), rear)
- Main rudder
- Lower left-wing
- Right-wing minor

The damage is now located (for example) in the lower left-wing. A structure is re-divided into:
- Left-wing,
- Right-wing,
- Body of the aircraft (the larger cylinder) divided into 3 parts (front, middle (crimping of the wings), rear)
- Main rudder
- Right-wing minor
- Lower-left wing, with fine discretization (on a hierarchical approach).

The latest was the successive divisions of region, like the dynamic growth of a tree: with probabilistic branching - occurring if and only if there was damage on the node in question.

The generation of simulated damage for analysis of results was thus developed:

Take up a square matrix (order N) completely filled with 0. Come up each element, changing the 0 to 1 with probability p. Make the following analogy: 0 no damage, 1 the presence of damage. The probability p is, therefore, the density of damage.

Once built the fundamental matrix of damage, was done a local grouping. The value of each element of the matrix "top" is null if and only if all near elements of the matrix "lower" are null. Figure 4 illustrates this procedure, for p=2, N=27, 3 levels, and grouping of 9 elements (square with side equal to 3).

4. Preliminary Results and Discussion

4.1. Testing the hierarchical approach

Got a square matrix (like the discribed in the last section). This is the first discretization. For each element, if the element is null is not necessary continue with the discretization, it
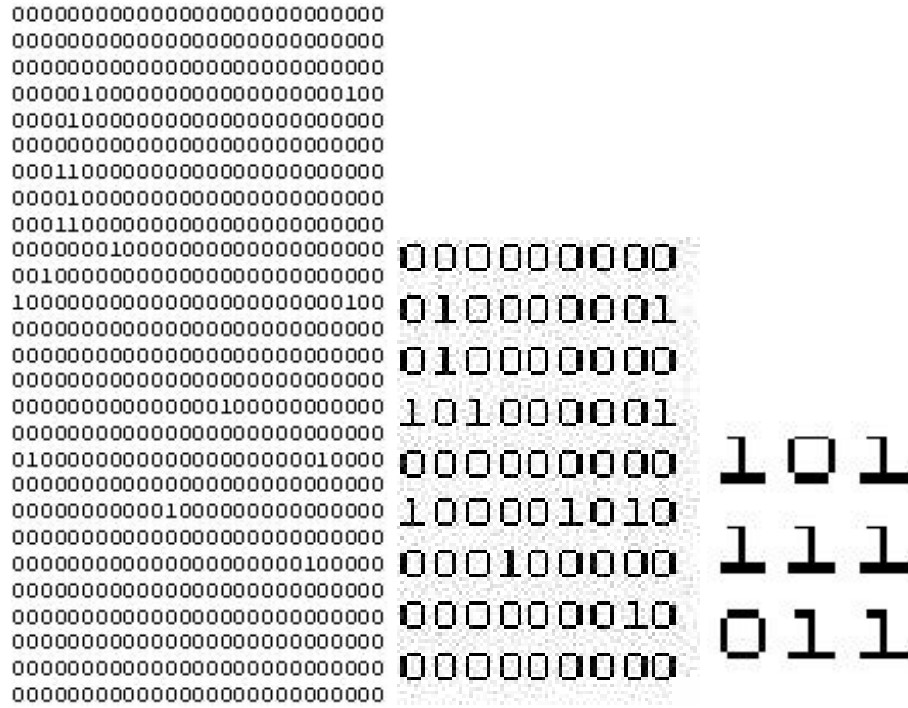
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Figure 4. Local grouping

symbolizes putting 2 in the matrix element result (below). If the element is one, this point create a branch (breadth-first): the discretization must go on. The procedure is therefore dynamically create branches only when the element on analysis present the value one (Figure 5).

The criterion for stopping is given by the size of the lower division (acceptable precision for the detection of damage).

The cost of this approach is the number of evaluations of elements:

$$cost = \sum_{n=1}^{INT(\log(V)/\log(r))} INT(r^{n+1} \min(1, p\, r^{1+(\log(V)/\log(r))-n}))$$

Where:

n: each level of the tree.
V: number of elements of the finest discretization (accuracy of the sensors).
r: number of branches of each node.
p: density of damage (number of elements with damage divided by the total number of elements).

Therefore, as higher r as higher the cost, then the best tree is the binary type. The cost is linear in V and in p, and exponential in r. These results supports the application of the methodology to large structures. Calculating the computational time for the hierarchical approach and exhaustive approach is possivel to observe that the first took only forty percent of the computing time of the second way.

5. Conclusions

The hibrid approach to solve the inverse problem of mechanical vibration was proposed in Chiwiacowsky, 2005 [2]. To work eficiently with large estructures, with bilions of degrees
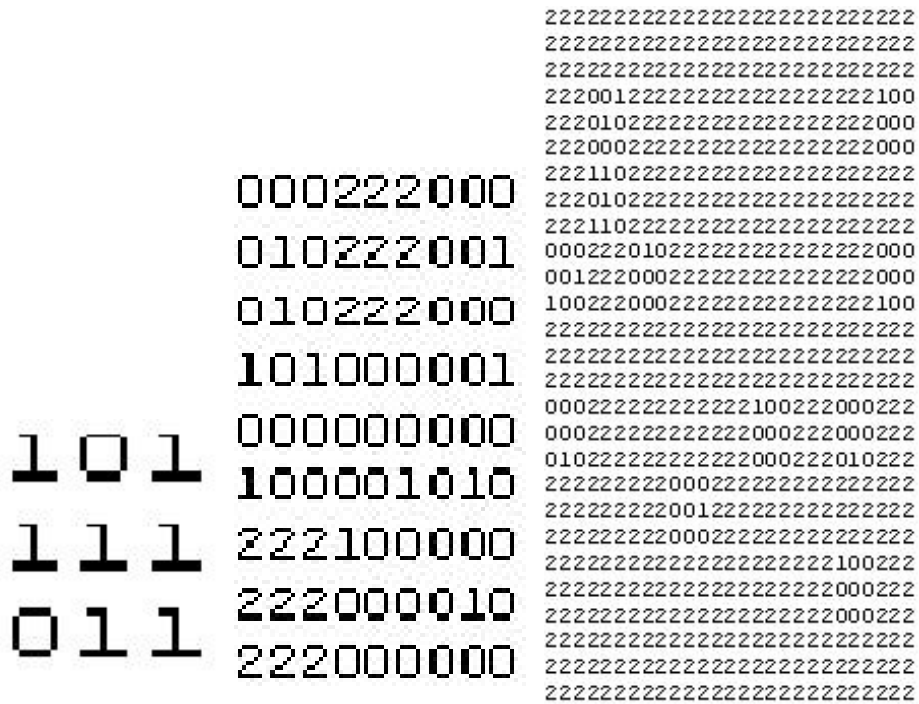
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Figure 5. Hierarchical search of damage

of fredom, it is necessary some upgrades on the metodology. These upgrades should be done with the use of a parallel GA, like the proposed in Sambatti, 2004 [3], and with a new approach for the search of damage. The initial results of that research have been shown the eficacy of the hierarchical approach, on a academic problem (without noisy).

In case of random distribution of damage, the best tree is the binary type, presenting a linear behavior of the cost (algorithm's complexity) against the number of items in the structure - showing the robustness of the methodology when applied to very large structures. On a structure of a million of elements, with density of random damage of one percent, the hierarchical search takes only forty percent of the computing time agreed to the classical search to provide the same results on an academic noisyless test.

6. Perspectives

As already verified the feasibility of the hierarchical approach, the next step is to work with a homogeneous beam, without noise. This test is the reproduction of the previous, but now really using the inversion method (quantitative study). After this step, the case-study is based on data from the application on the ISS [11], comparing efficacy and efficiency with and without the parallel GA and with and without the hierarchical approach.

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