INVERSE PROBLEM IN DAMAGE IDENTIFICATION OF A HELICOPTER'S ROTOR BLADE USING BAT ALGORITHM

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Abstract. In this study, a damage detection method is proposed using the bat optimization algorithm and vibration data simulated in CAE software. The method was applied in a helicopter rotor blade based in the AS350's rotor blades. The rotor blade was modeled and simulated in ANSYS APDL®, the modal solution was exported to MATLAB® and then the algorithm was applied to optimize the objective function defined by the authors. Three objective functions of displacement in the three axis were used and theirs results were compared. The numerical results show that the method is reliable and adequate for practical application in the industry.
Keywords: Damage Identification; Inverse Problem; bat algorithm; helicopter blade; Structure Health Monitoring; damage detection;

1 Introduction

The aeronautical and Aerospatiale industry have great interest in damage detection area in structures. A technology capable of identifying the exact point of a crack in the aircraft can generate great economy and improvement of the system's reliability.

Rytter [1] describes the damage identification methods. In a first level, we have the visual methods. With these, it's possible detect macroscopic damage in the external structures by direct visualization and in internal structures by viewing windows. However, this type of damage is easy to detect, the great difficulty appears in the detection of tiny cracks that can evolve quickly to a structural catastrophic failure.

There are also the so called experimental or local methods, they use various tools like ultrasounds, radiographies, eddy-current, and thermal field, Doherty [2]. Despite being efficient in the detection, they need the previous knowledge of the crack regions, but in real situations this information is almost always unknown.

There are also the global methods, they made a deeper analysis in the structure and by simulations can give the exact crack's location using softwares like ®ANSYS, saving a lot of time for the analysis.

Furthermore, we can classify the types of damage detection in levels, as is proposed by Rytter [1].

Level 1 – Recognition of the damage's presence;

Level 2 – Damage's area identification;

Level 3 – Measurement of the damage's severity;

Level 4 -Remaining useful time estimate.

It is worth mentioning that the level 4 of detection is the great challenge for the composites today. Composite materials are different from metals as they don't have a unidirectional behavior for the cracks. Composite's cracks normally contour the fiber and affects the adherence with the matrix. As these materials are increasingly presents in the industry, its essential to study this behavior.

All these different methods are classified as a new field of study in the structural engineering, the Structure Health Monitoring (SHM).

2 Objectives

This work had as objectives to study important tools in the engineering, as software like ®ANSYS and ®MATLAB, and as mainly goal, implement an effective global damage detection method.

3 Theoretical background

3.1 Vibration based damage detection methods

Such methods use vibration modal analysis to interpret the collected data of the structure, this means, through frequency, damping and modal information.

This method assumes that modal parameters (frequency, vibration modes and damping coefficient) are functions of the structure's physical properties as masse, stiffness and damping, Doebling et al [3].

Thereby, if there is damage in the structure, no matter how small, this crack will generate a reduction in global stiffness. By Hooke's law, if the stiffness changes, so the displacement. The structure's vibration being a small displacement, there will be changes that can be detected.

3.2 Frequency variation based methods

The frequency-based methods are the most studied nowadays, we analyze the global frequency changes. This method, however, rarely passes the first level of detection, a lot of precision measures or a severe enough damage to reach the level 3 of detection. Doebling [3] mentions as example oil rigs where is very difficult to distinguish variations caused by damage or mass increase (caused by sea's oxidation). In general terms, the procedure consists in identifying the frequency range in known cracks, if this pattern is identified in another structures, the damage's existence is confirmed.

Santos [4] describe this method applied for composites. A Frequency spectrum is identified for different cracks in different vibratory modes, and these are compared with experimental values, generating another group of average values, creating a model. Finally, this model is applied in a whatever structure to identify the probable location of the damage.

3.3 Strain Energy based methods

Vo-duy *et al*. [5] affirms that meta-heuristics optimization methods as *genetic algorithm* (GA), *particle swarm optimization* (PSO), *artificial bee colony* (ABC) despite having good results, have a high computing cost, are limited by the number of variables and are not adequate to composites.

Therefore, is proposed the strain energy method. The strain energy is defined as the energy generated by the deformity caused by external forces, thus, if there are variations there was deformation in the structure. This method is supplemented by differential evolution algorithm to find the damage's extension.

3.4 Damping based methods

With the advances of damage detection and the limitations of the frequency-based method. Modena *et al[6].* shows that damages that cause minimal variations in the frequency-based method, in contrast, generate high variations in damping properties, 50% variations were observed. Curadelli *et al [7].* propose a new detection system, with a similar procedure as in the frequency method but changing the input data, using the damping coefficient and the wavelet transform to interpret the data.

3.5 Structure health monitoring in the aeronautical field

SHM studies begin in the early 70's, in the oil industry, due the operational conditions of the off-shore oil rigs, BEGG *et al.* [8]. In the following years, this field of study was well absorbed by the construction industry.

Nowadays, there is an increasingly interest for SHM by the aerospace industry, for this one has the strictest security criteria. Modlin e Zipay [9] studied the aviation safety factor, due to the lowest weight possible requirement, this industry works with a small factor if compared with the others, about 1.5. In addition, this factor doesn't remain continuous in all service life of the aircraft, thus, it is necessary a high rigor in its structure's maintenance. It is important to note that in the main use of aircraft, airlines, the profit is essential, and for that is ideal that the aircraft stays operational as possible, with the necessary maintenance, nothing more, GOLBE [10]. In this context, new method of SHM are essentials, more specifically, global methods as presented in this work

Going further, the rotorcraft industry has even bigger interest in SHM. Rotor blades are submitted to serious efforts and various types of damages: Impact damage, matrix cracks, delamination and damage due imbalance, SANTOS *et al [4].* Therefore, for these reasons it is necessary to have a quick and efficient method to monitor the structure.

3.6 Bat Optimization Algorithm

The BOA is inspired in the microbat's behavior and their ability of echo-localization. This algorithm uses as parameter the loudness and the pulse, it was the first to consider the frequency tuning.

The BOA has a mutation capability due to his frequency tuning that increases the velocity of finding the global optimal value, YANG [11].

4 Developed activities

4.1 Direct Problem.

The rotor blade studied was based in the AS350's rotor blade, having the same airfoil and dimensions, taken from the aircraft's manual. To simplify the model, the geometric twist was considered. Moreover, just the rotor blade's skin was modelled. Stringers, ribs and internal foam were not taken into account.

About the material, is a glass fiber laminate with 12 layers of 0.18mm thickness, with the following properties:

- Especific mass: 1408.8 kg/m³;
- Ex: 83.015 Gpa
- Ey: 5.13 Gpa
- Ez:5.13 Gpa
- Poisson's factor: 0.3208
- Gxy: 8.37 Gpa
- Gyz: 1.94 Gpa
- Gxz: 8.37 Gpa.

For the rotor modeling, first was ploted the root and bladetip airfoil and support points.

Figure 1 – Airfoil points

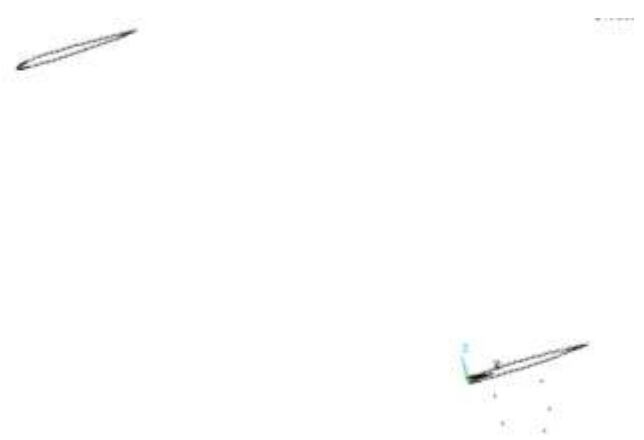


Figure 2 – The points in 3d vision

Thenceforth, it was created lines that by the command "extend line" could be transform in areas.

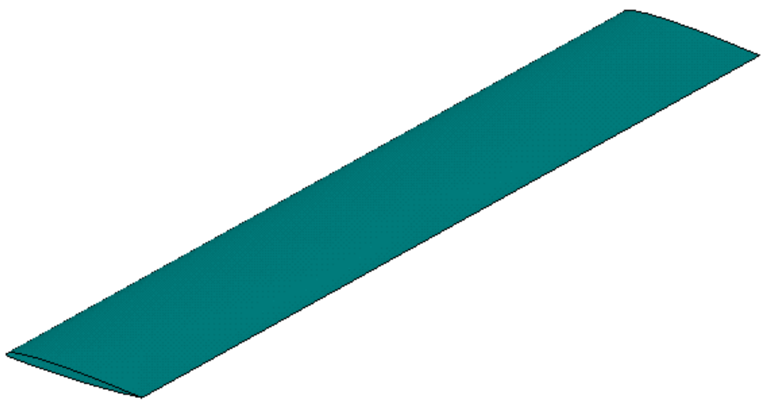


Figure 3 – Rotor blade's aerodynamic part

For the support, there is a difference in the transverse section, of an airfoil section to a rectangular section. To create these areas, it was used the *skinning* function. After the transition, the support continues in rectangular section of 120x70 mm with 250mm length.

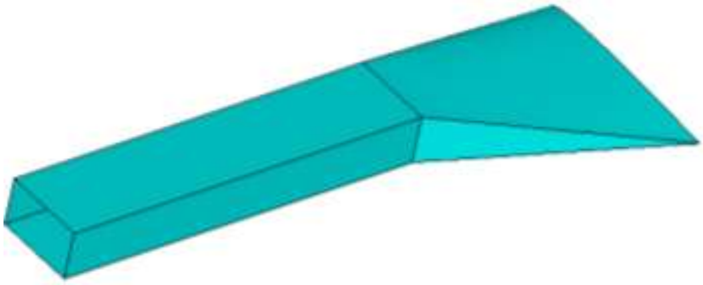


Figure 4 - Support

The combination of these 2 parts generates the following assembly:

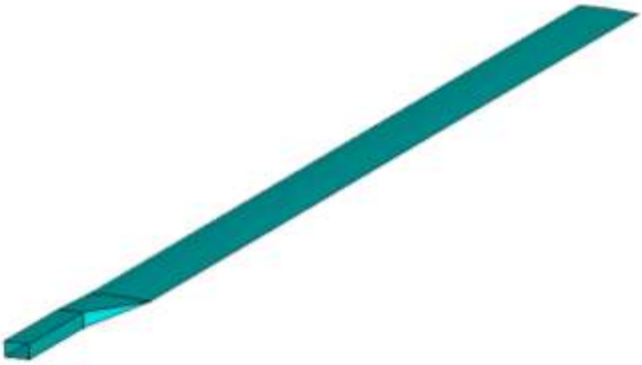


Figure 5 – Complete rotorblade 3D

Figure 6 – Rotorblade top view

Figure 7 – Rotorblade side view

With the rotor blade properly modelled, it was meshed. In software CAE, it was chosen the element SHELL281 with a *quadratic mapped* mesh.

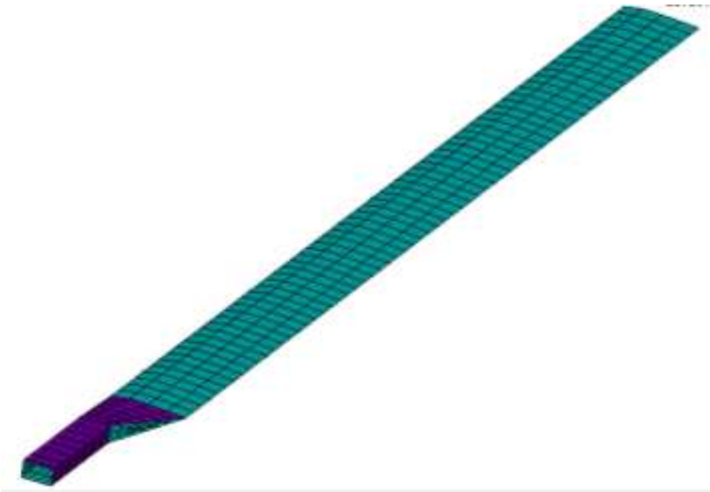


Figure 8 – Meshed rotorblade

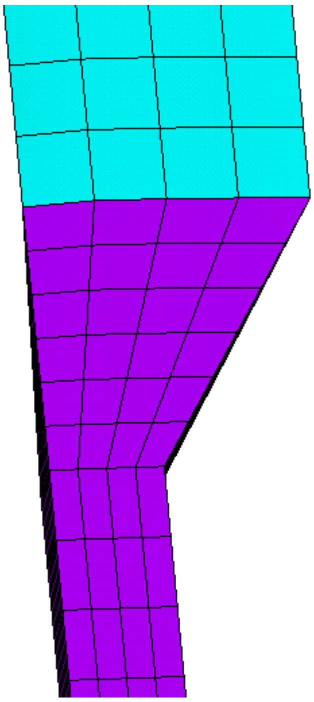


Figure 9 – mesh detail

With the rotorblade properly modelled and meshed, it was made the modal analysis in free vibration, fixed by its support. It was calculated the first 6 modes in the 3 axes. The results are presented in chapter 5.

4.2 Inverse Problem

In this work, it was modelled 10 sensors in the rotorblade equally distributed in its aerodynamic area. These sensors collect displacement data in free vibration

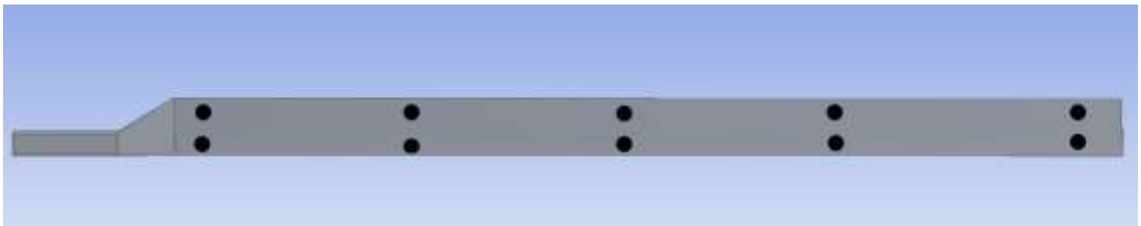


Figure 10 – Sensor's locations

The objective function is the equation to be optimized by the algorithm. In this case, it was used the relation between the measured values and optimized ones. 3 different equations were used, each one in a Direction of displacement.

$$J1 = \sqrt{\frac{1}{n}\sum\left(1 - \frac{\Phi_{\mathrm{x}}^{\mathrm{real}}}{\Phi_{\mathrm{x}}^{\mathrm{otimizador}}}\right)^2} \tag{1}$$

Equation 1 – Objective function x axis

$$J2 = \sqrt{\frac{1}{n}\sum\left(1 - \frac{\Phi_{\mathrm{y}}^{\mathrm{real}}}{\Phi_{\mathrm{y}}^{\mathrm{otimizador}}}\right)^2} \tag{2}$$

Equation 2 – Objective function y axis

$$J3 = \sqrt{\frac{1}{n}\sum\left(1 - \frac{\Phi_{\mathrm{z}}^{\mathrm{real}}}{\Phi_{\mathrm{z}}^{\mathrm{otimizador}}}\right)^2} \tag{3}$$

Equation 3 – Objective function z axis

Objective functions defined, it was initiated the optimization process in MATLAB® with the BOA algorithm. The parameters were the following:

n=80; Population

A=0.25; loudness

r=0.50; Pulse rate

Iterations = 100;

The optimizer is composed by 4 programs: The first contains the objective function, the second contains the algorithm, the third the bound checking, and the last is the one that is actually executed, and does the damage detection.

Each iteration, the optimizer opens the MEF software and imports new results to make the calculations. Each result's iteration is presented in a graph, with the element number horizontally and severity vertically.

The bats are also represented, showing the convergence. The optimal value is marked with a red circle. The graph is presented in the figure 11.

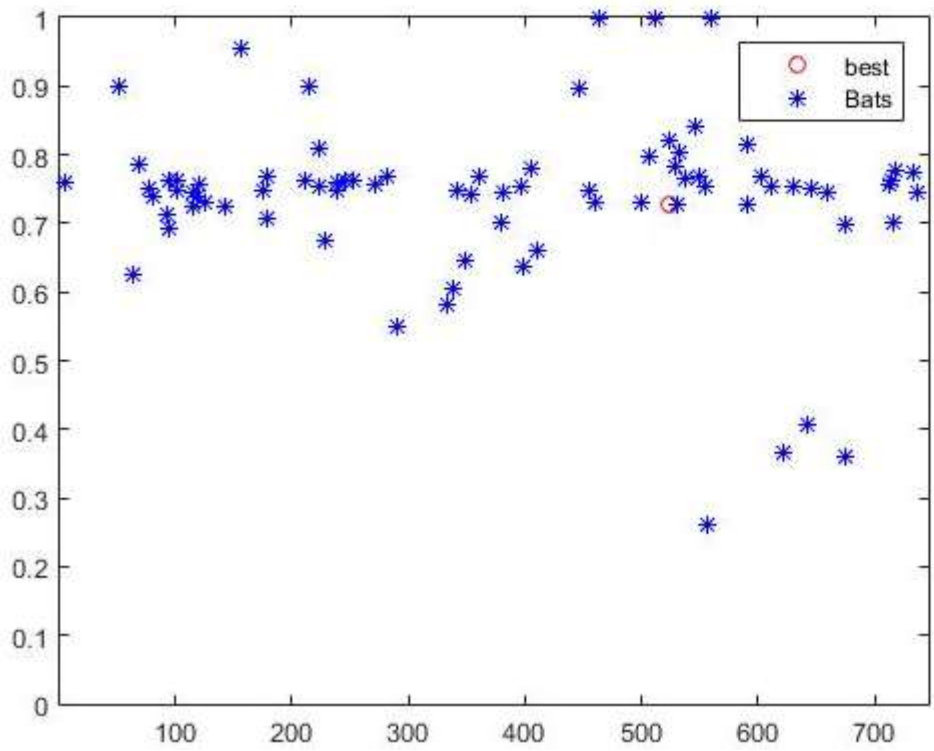


Figure 11 – Results graph

5 Results and analisys

It was defined a new analysis and the modal option chosen; it was calculated the first 6 modes. The table 1 represents the results for the undamaged rotor blade, and the table 2 the results for damaged rotor blade.

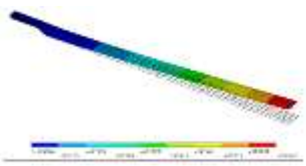
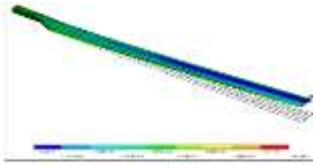
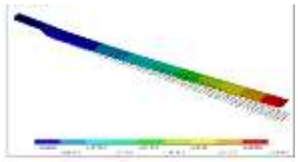
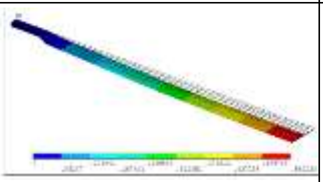
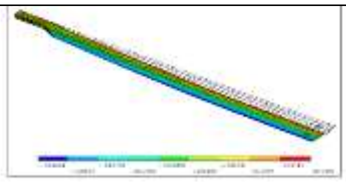
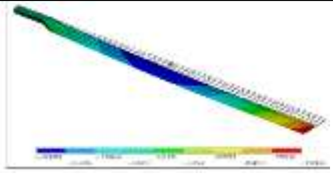
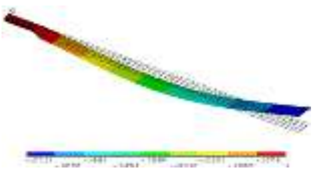
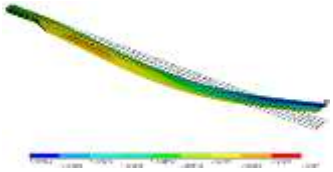
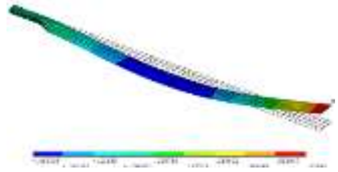
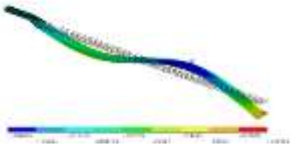
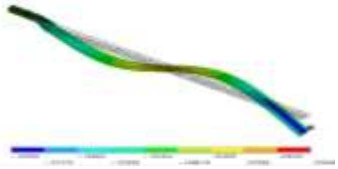
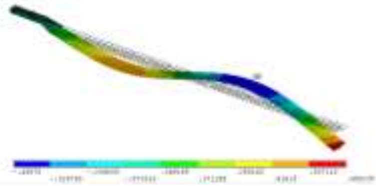
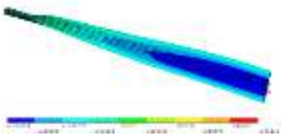
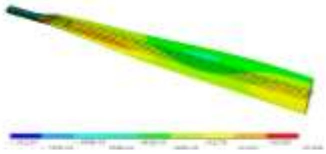
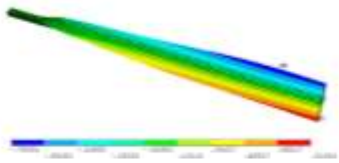
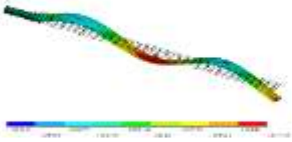
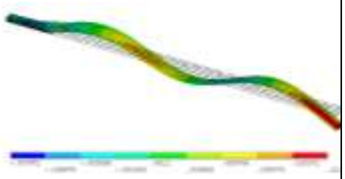
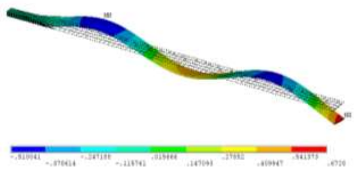
	Natural Frequency(Hz)	Mode x	Mode y	Mode z
Mode 1	0.70076			
Mode 2	4.2602			
Mode 3	4.6212			
Mode 4	12.874			
Mode 5	17.071			
Mode 6	24.369			

Table 1 – Modal results without damage

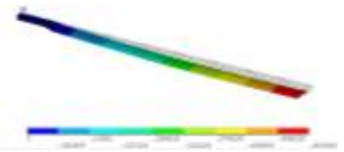
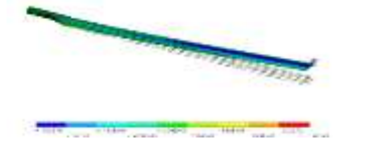
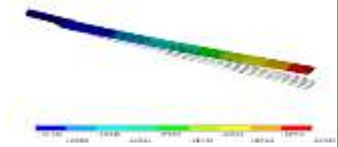
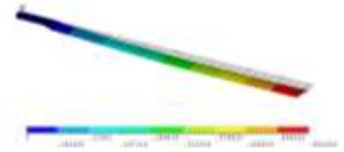
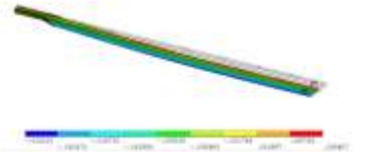
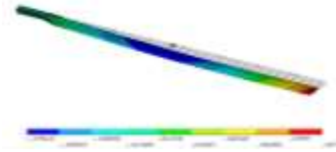
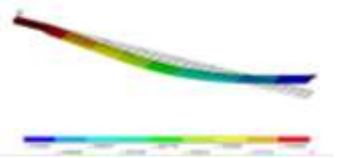
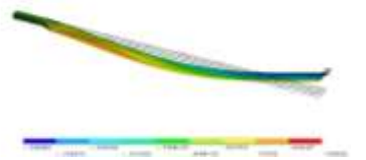
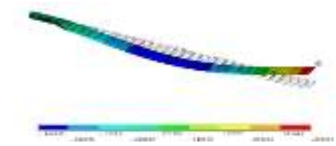
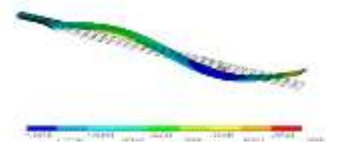
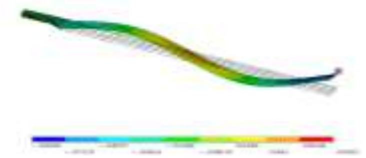
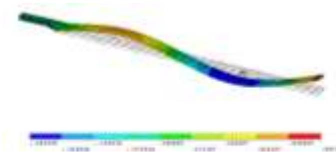
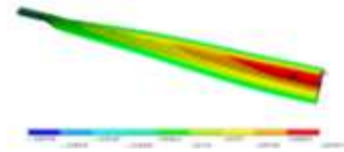
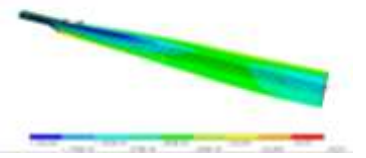
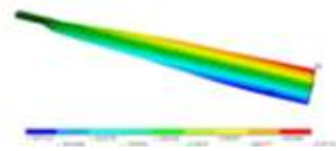
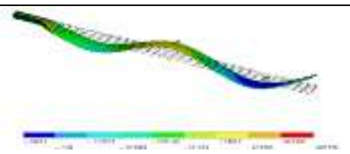
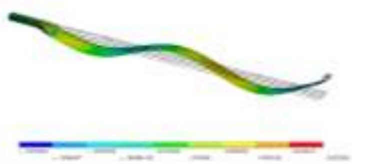
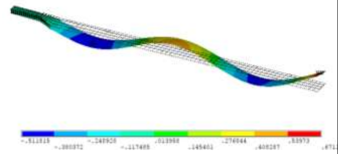
	Natural Frequency (Hz)	Mode x	Mode y	Mode z
Mode 1	0.69986			
Mode 2	4.2609			
Mode 3	4.6094			
Mode 4	12.866			
Mode 5	17.027			
Mode 6	24.327			

Table 2 – Modal result with damage

The induced damage in this comparison was on the element 153 with severity damage of 0.1. Analyzing the results, we note a little difference in terms of natural frequency and displacement, but a significant difference in the modes, as in the 6º mode z direction.

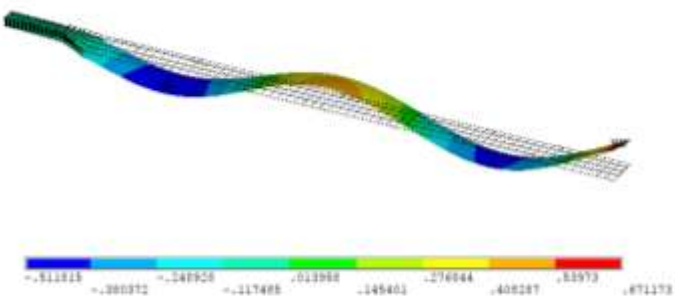


Figure 12.a – Undamaged rotorblade

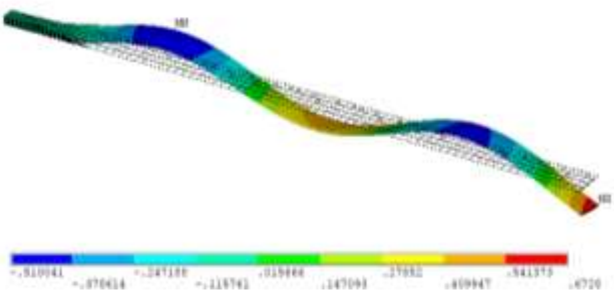


Figure 12.b – Damaged rotor blade

5.1 Optimizer Numerical results

For each objective function and induced damage, the algorithm was run 10 times, and for these results, it was calculated the average severity and the mode for the damaged element.

It was also calculated the standard deviation for the severity

CASE 1						
	Ne	**α**	**Ne**	**α**	**Ne**	**α**
Objective	153	0,1	325	0,2	520	0,5
Run 1	149	0,145	342	0,29	520	0,5
Run 2	153	0,1	325	0,19999	520	0,5
Run 3	149	0,146	325	0,2	520	0,4999
Run 4	153	0,1	338	0,37	525	0,4899
Run 5	133	0,34	317	0,1522	523	0,65
Run 6	153	0,1	325	0,2	531	0,6
Run 7	149	0,1445	325	0,2	430	0,2955
Run 8	153	0,0999	338	0,37	527	0,6279
Run 9	149	0,1445	325	0,2	520	0,5
Run 10	149	0,1446	325	0,2	520	0,5
Mode	**149**	**0,14645**	**325**	**0,23822**	**520**	**0,51632**
Desviation	**5,96285**	**0,07158**	**7,94775**	**0,07716**	**29,6168**	**0,09895**

Table 3 – J1 function results

CASE 2						
	Ne	**α**	**Ne**	**α**	**Ne**	**α**
Objective	153	0,1	325	0,2	520	0,5
Run 1	153	0,1	321	0,1579	524	0,6721
Run 2	141	0,2993	321	0,158	520	0,5
Run 3	153	0,1	313	0,04799	534	0,9753
Run 4	157	0,119	342	0,3053	530	0,9421
Run 5	157	0,12	346	0,2634	518	0,4939
Run 6	157	0,119	321	0,158	520	0,5
Run 7	153	0,1999	325	0,2	530	0,9421
Run 8	157	0,012	346	0,2633	524	0,6721
Run 9	145	0,2429	342	0,3052	616	0,3602
Run 10	153	0,1	338	0,3916	524	0,6721
Mode	**153**	**0,14121**	**321**	**0,22507**	**524**	**0,67299**
Deviation	**5,48128**	**0,083**	**12,4655**	**0,09945**	**29,2575**	**0,21756**

Table 4 – J2 function Results

CASE 3						
	Ne	**α**	**Ne**	**α**	**Ne**	**α**
Objective	153	0,1	325	0,2	520	0,5
Run 1	153	0,1	313	0,0588	520	0,5
Run 2	153	0,09999	321	0,1637	520	0,4999
Run 3	157	0,1	325	0,4154	520	0,499
Run 4	153	0,09999	325	0,2	520	0,4999
Run 5	149	0,09999	325	0,2	520	0,5
Run 6	153	0,1	325	0,1999	520	0,5
Run 7	626	0,26	338	0,4153	520	0,5
Run 8	626	0,26	329	0,132	520	0,4999
Run 9	153	0,09996	313	0,588	520	0,4999
Run 10	153	0,09996	338	0,4154	520	0,5
Mode	**153**	**0,13199**	**325**	**0,27885**	**520**	**0,49986**
Deviation	**199,443**	**0,06747**	**8,5479**	**0,1678**	**0**	**0,00031**

Tabela 5 – J3 Function Results

The following figures shows the physical locations of the induced damage and the ones found by the optimizer. We can observe great precision in finding the damage's region.

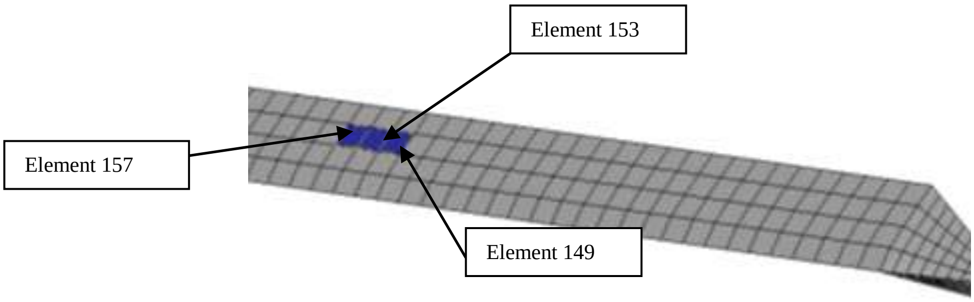


Figure 13- Damage found case 1

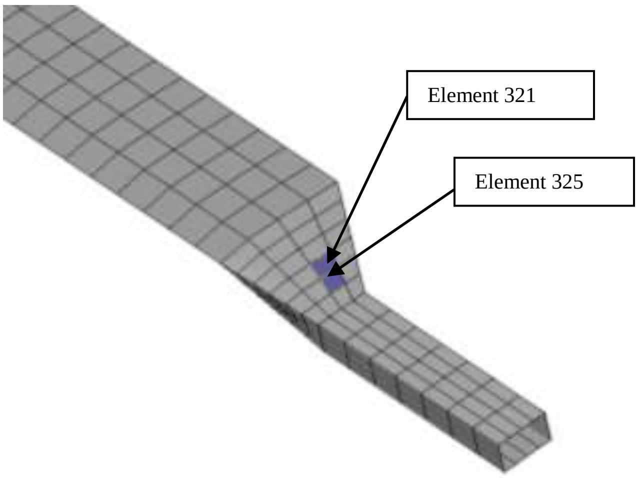


Figure 14- Damage found case 2

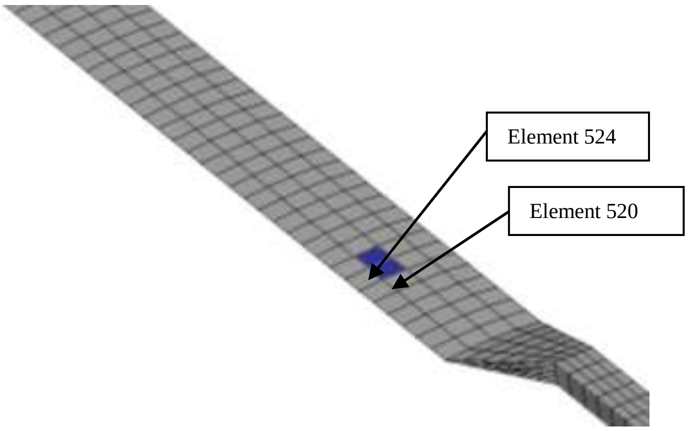


Figure 15- Damage found case 3

6 Conclusions

This work proposed the implementation of a nature-inspired algorithm in a damage detection inverse problem. The studies object was based in a real helicopter rotor blade, widely used in the industry. The undamaged and damaged model were compared by a objective function based in displacement data simulated. The algorithm was implemented to optimize the objective function, in the 3 normal directions.

The results show good accuracy to find the damaged element, when this is not exactly found, there was little difference, finding the element just on the side. It was observed that the J3 function, in z axis, had the better accuracy, having a standard deviation of 0.031% when finding the third damage's severity.

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