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FREQUENCY RANGE OPTIMIZATION BY THE USE OF ACO AND BCO METHODS IN THE IMPEDACE-BASED SHM

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Abstract. *In the last years, the number of studies of SHM (Structural Health Monitoring) is increasing as an important field of Civil, Mechanic and Aeronautic Engineering. The Impedance-based technique is one of them and one factor to be chosen is because of the non-destructive aspects. According to this technique, real structure signatures are gathered in a pristine condition as such as in a damaged status. It was used in the experiment the following resources: an aluminum beam, a PZT patch, a magnet piece (in order to simulate the damage) and one AD5933EBZ evaluation card for the data acquisition. The aim of this contribution is to find the most sensitive frequency range to monitoring damages. Then, finding this frequency range is possible to create a model for damage detection purposes. Two bioinspired optimization methods were used in this study: Bee Colony Optimization (BCO) and Ant Colony Optimization (ACO). In both cases the objective function was the damage metric proposed by the impedance SHM technique. Results from both methods indicate the same best frequency range comparing the baseline and damage condition.*

Keywords: *Bee Colony Optimization, Ant Colony Optimization, Impedance-based Structural Health Monitoring.*

1. INTRODUCTION

Structural Health Monitoring (SHM) and Non-destructive evaluation (NDE) technologies have been the focus of several both academic and industrial fields along past recent years (Rabelo *et al.*, 2016). Both have the same foundations and features concerning to the sensors and data gathering. However, SHM has a more pragmatic aspect compared to the NDE due to the embedded integration of the sensors/actuators (smart materials) in the monitored structure (Afshari, 2012).

The main aspect of a NDE technique is to not produce changes in the studied structure in order to have the same condition after the evaluation was completed. Nowadays, there are several NDE techniques as such as eddy-current, magnetic-particle, radiographic testing, liquid penetrant inspection, ultrasound and visual testing (Bray and McBride, 1992; Palomino, 2008; Tsuruta, 2008; Moura Júnior, 2008; Leucas, 2009).

Thus, industry is increasing the use of some of them in the predictive maintenance approach, applying them in machine and structure monitoring and others (Furtado, 2004). Such use in the shop floor industry is justified because the cost reduction aspect due to the safety assembling/disassembling of structural components and increasing the reliability of structures and equipments (Farrar and Worden, 2012).

SHM (Structural Health Monitoring) is a group of techniques aiming the monitoring or detection of damage in structures (Moura Júnior *et al.*, 2008). Impedance-based structural health monitoring is based on the signal analysis in a high frequency level by the use of a piezoelectric patch bounded onto the surface of the studied structure. In a high frequency range is possible to identify cracks, little holes and small damages (Bray and McBride, 1992; Palomino, 2008; Afshari, 2012).

According to Park *et al.* (2003), Impedance-based Structural Health Monitoring uses the piezoelectric property of the materials proposing a new NDE technique. The basic concept of this technique is the monitoring of the variation of the mechanical structure impedance in higher frequencies (above 20kHz), which can change in the presence of small damages. Once the straight mechanical impedance of the structure in higher frequencies is a hard task, this technique uses PZT patches bonded in the surface of the structure or embedded, enabling the electromechanical impedance gathering. This measured electro-mechanical impedance changes in higher frequencies can be associated to the occurrence of damages. One important assumption is the sensor/actuator stands in a pristine condition (Park *et al.*, 2003; Palomino, 2008; Bitencourt and Steffen Júnior, 2009).

Some other variables could cause changes in the mechanical impedance of the structure. One of them is the environment temperature or external source of vibrations. The properties of the PZT patch, as well as the Young's modulus of the studied structure could also change in extreme temperature changes. Thus, the impedance-based structural health monitoring technique can shows variation in signatures in environment temperature changes, but in fact, there is no damages occurring (false positives). There are some studies in SHM to compensate this aspect but this is not the focus of the work (Rabelo *et al.*, 2016).

In the impedance-based SHM is important to observe that the electrical admittance is basically capacitive, where the imaginary term is dominant. The imaginary part is more sensitive to environmental factors (as such as temperature) than the real term that is associated to the mechanical impedance. Then, the real part is usually used in the impedance-based SHM applications (Raju, 1997; Park *et al.*, 1999; Park, *et al.*, 2000; Koo *et al.*, 2009; Afshari, 2012).

The impedance sensors/actuators (PZT patches) are able to monitoring the main mechanical features of the structure as such as mass, stiffness and damping due to the dynamics measurement of the electro-mechanical impedance (Palomino, 2008). The PZT patch was the first sensor/actuator used at the beginning of the development of the impedance-based technique and still in use due to the wide range of linearity, lightweight, fast mechanical response, low cost, stiffness greater than the stiffness of the structure in study (Park *et al.*, 2003; Bitencourt and Steffen Júnior, 2009). Because the stiffness of the PZT patch is greater than the stiffness of the structure in evaluation, the electromechanical conversion occurs in a high efficiency, becoming the PZT patch very efficient to applications of control and damage detection in wide frequencies (Banks *et al*., 1996).

According to Moura Júnior (2008), in general, there are vantages and disadvantages in the use of the piezoelectric components. The main advantages are: works very well in low temperature changes (human environment), linear response in a low voltage excitation, lightweight, wide work frequency range and available in different dimensions. The main disadvantages are: difficult to cut (ceramic material), hysteresis in higher electrical fields, in a long term can present the polarization decay reducing the piezoelectric behavior.

Compared to the traditional modal analysis experiments, the impedance-based SHM works in very high frequencies of excitation. Thus, the dynamics response of the technique represents only an area of the structure very close to the sensor/actuator. The mechanical response of the excited area promoted by the vibration close to the PZT patch is gathered as an electrical response. Then, the structural change can be measured by the technique in about 0.4 meters (radial distance) in composite structures and about 2 meters in single metal beams (Park *et al.*, 2003).

Figure 1 represents an example for a better understanding of the electromechanical impedance-based SHM model, by the use of a single mass-spring system with one degree of freedom.

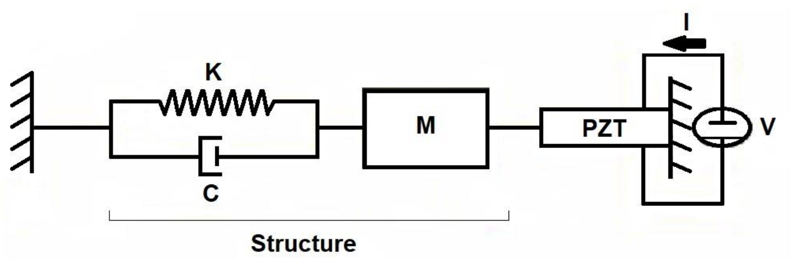

Figure 1: One-dimensional model of electromechanical coupling used in SHM based on electromechanical impedance.

According to Sun *et al*. (1995), the best frequency range to apply the impedance-based SHM technique is above 200kHz in order to find small damages while ranges lower than 70kHz are more appropriate to find greater ones. In general, the equipment used for data gathering is an impedance analyzer and data are measured and transferred to a computer for further modeling and evaluation.

1.1 Bee colony optimization

In the past few years, some new optimization techniques are developing in terms of new approaches as well as implementation approaches, mainly in heuristics based on biological systems. These methods are different from the classical techniques because create a population of potential solutions to the problem and investigate the best answer by a specific strategy (heuristic) and further update of this population. It is necessary to highlight that this interaction among the individuals frequently conducts to some kind of behavior or collective intelligence. This feature is the Mathematical basis of the search for the optimal solution in bioinspired algorithms (Serapião, 2009).

The BCO (Bee Colony Optimization) Algorithm was proposed by Lucic and Teodorovic (2001) to solve combinatory optimization problems. This method is based on the search of bees by the raw material to produce honey. After some observations of the nature, Lucic and Teodorovic (2001) noted that the bee colony could fly for long distances (about 10 km) and in different directions at a same time searching for sources of food. Then, the bee colony algorithm is based on this phenomenon: communication methods, information sharing by the sound, pheromones, tact, dances and electromagnetic stimulus (Lucic and Teodorovic, 2001; Serapião, 2009).

1.2 Ant colony optimization

The ACO (Ant Colony Optimization) Algorithm was proposed by Marco Dorigo and others at the beginning of the 1990 as a new bioinspired proposed model (Dorigo *et al.*, 1991).

According to Koide (2010), the Ant Colony Optimization (ACO) was inspired in the ant behavior, regarding to the work organization, cooperation and about the search for food. Bug colonies are very organized and collective tasks are conducted under a self-organizing way. This social behavior of the bugs can be explained as a dynamical mechanism of interaction system of their components. The social self-organizing study of the bugs applied as instrument to other fields of knowledge promoted several intelligent system projects with such features, as such as ant colony algorithm (Bonabeau *et al.*, 1999).

The self-organizing system of the ants needs an interaction among them. This can be in a direct way, by tact: antenna, visual and chemical contacts. Also, this can be in an indirect way by modifying the environment and another individual answering to this change in the future (Bonabeau *et al.*, 1999).

The indirect communication among ants is based on the pheromone, a chemical substance produced by the (Dorigo and Stützle, 2004). Some species uses the pheromone to make paths and guide other ants to a source of food. The observation about the pheromone was done by Deneubourg *et al*. (1990), by using real ants of the *L. Humile* specimen.

2. EXPERIMENTAL PROCEDURE

The conducted experiment to obtain the impedance-based SHM signatures used an aluminum beam and two conditions of the structure were monitored. First, it was conducted a pristine condition of the structure to be used as baseline. Then, a second condition of the structure with a simulated damage (mass addition with a magnet) is gathered.

It was used the Eval AD5933EBZ card as the impedance data acquisition system. This card has the CI AD5933 and has an analogic-digital converter and a microcontroller conducts internally the DFT (Discrete Fourier Transform), operating with 2.7-5.5V (can be power sourced by a common USB port). This card gathers the magnitude and phase of the impedance signature which the real part to be used in the SHM technique can be obtained (Sepehry *et al.*, 2011; AD, 2017).

Figure 2 illustrates the data acquisition system used in the experiment.

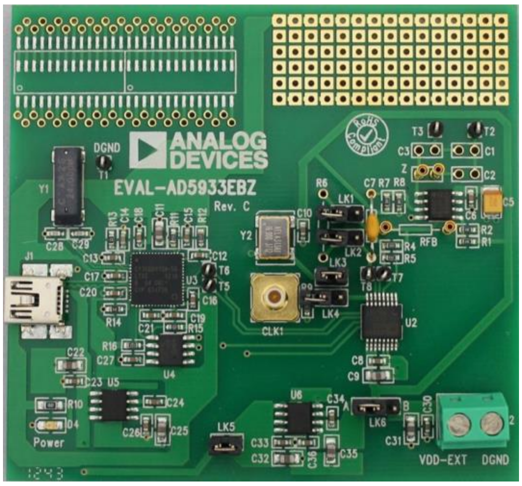

Figure 2: Evaluation board *EVAL-AD5933EBZ*.

The card communicates to the computer by USB connection and uses the software “AD5933 Evaluation Board Software Rev.B” supplied by the manufacturer for gathering purposes. Although the measured impedance is important to define the status of the structure, this information needs to be processed before.

Different statistics methods are used in the impedance-based SHM in order to create useful indexes. Then, damage metric used in this contribution was presented initially by Sun *et al*. (1995) and it is described as the RMSD (Root Mean Square Deviation) and is presented in the Eq. (1) (Afshari, 2012; Tseng and Naidu, 2002).

$$M = \sum_{i=1}^{n} \sqrt{\frac{(\mathrm{Re}(Z_{i,1}) - \mathrm{Re}(Z_{i,2}))^2}{(\mathrm{Re}(Z_{i,1}))^2}} \tag{1}$$

where M represents damage metric, $Z_{i,1}$ represents the baseline measured signal, $Z_{i,2}$ means the damaged condition in the i frequency and n indicates the number of frequency evaluated. Thus, for a greater value of M, greater would be the difference between both signatures (Moura Júnior, 2008).

A first procedure to make the damage detection is to find the best frequency range to be monitored. Thus, here are presented two different bioinspired approaches (ACO and BCO) to find this best range due to the damage.

The aluminum beam used in this study has 300x25x3mm and the magnet that simulates the damage (Figure 3, inside red circle) has a diameter of 10mm and thickness of 3mm. The PZT patch bonded onto the structure has a diameter of 20mm and thickness of 3mm.

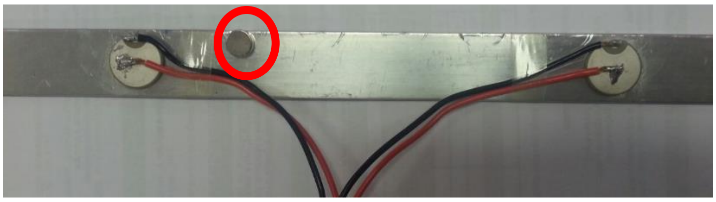

Figure 3: Beam with magnet (simulating failure).

3. RESULTS AND DISCUSSION

The evaluated frequency range was 50–65kHz in a step of 30Hz, presenting a total of 501 points. According to the references it was considered only the real part of the impedance signatures due to the mechanical properties were associated to them. It was gathered 20 samples of the pristine condition and 20 samples of the damaged structure. The average of these signatures is presented in Fig. (4).

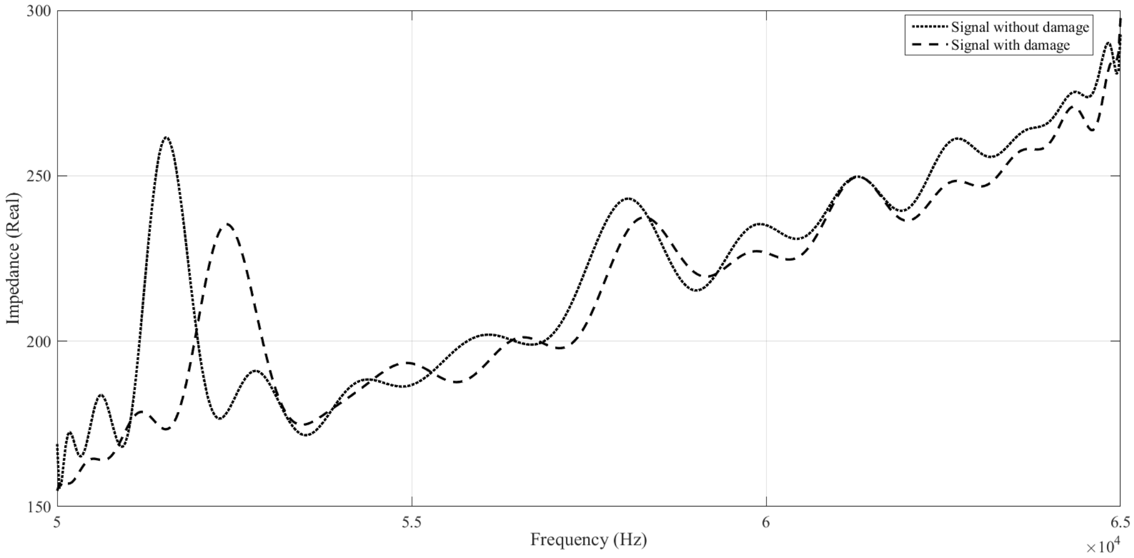

Figure 4: Complete frequency range of the experiment.

The objective function of the optimization procedure was the RMSD damage metric as the quantitative index and it was applied the same restriction about the frequency range: ±10 and ±20 points far from the middle point selected, i.e., the best frequency range can change between 21 and 41 points.

By the use of the ACO method, it was conducted some simulations with 5, 25 and 50 ants and 10, 25 and 50 iterations to check the effectiveness of the algorithm to find the best region of the signatures with greater differences. Table 1 presents the result of 15 simulations for 5 ants and 10 iterations. In all of them the frequency range selected has a vector of 41 points. It can be noted that with 5 ants and 10 iterations the result already converges to the position 65 in 14 out of 15 simulations.

Table 1. Simulations performed with the ACO to compare the optimal point with the population of 5 ants and 10 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	65	65	65	65	65	65	63	65	65	65	65	65	65	65	65
Range	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 2 presents the results of a population of 25 ants and 25 iterations, conducting 15 round of simulations. In all cases, the frequency range selected has a vector of 41 points. Also, a result of a model with 25 ants and 25 iterations converge to the middle point at 65 in all simulations conducted.

Table 2. Simulations performed with the ACO to compare the optimal point with the population of 25 ants and 25 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Range	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 3 presents the results of a population of 50 ants and 50 iterations, conducting 15 round of simulations. Comparing Tab. 5 results to the Tab. 4, all frequency range selected has a vector of 41 points. Also, a result of a model with 25 ants and 25 iterations converge to the middle point at 65 in all simulations conducted.

Table 3. Simulations performed with the ACO to compare the optimal point with the population of 50 ants and 50 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Range	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

From the presented tables, good results can be obtained starting with 5 ants and 10 iterations and the best result is obtained with 25 ants and 25 iterations. It is possible to conclude that the middle point (best point) is the 65 with a frequency range of 41 points, i.e., the best frequency range to evaluate the impedance signatures in study is 51320-52520Hz. Figure 5 shows the optimized range by the ACO.

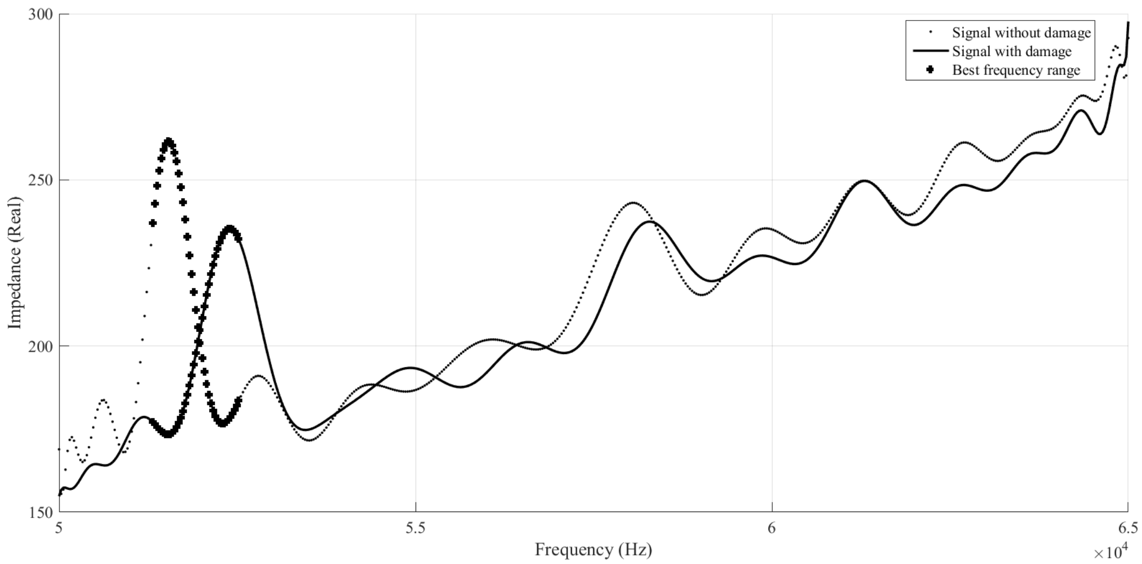

Figure 5: Frequency range optimized by ACO.

By the use of the BCO method, it was conducted some simulations with 5, 25 and 50 bees and 10, 25 and 50 iterations to check the effectiveness of the algorithm to find the best region of the signatures with greater differences. Table 4 presents the result of 15 simulations for 5 bees and 10 iterations. It is possible to check that with the selected range of number of bees and iterations, both middle point (best point) and range changes.

Table 4. Simulations performed with the BCO to compare the optimal point with the population of 5 bees and 10 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	71	63	62	72	65	64	71	65	65	64	72	61	63	57	85
Range	19	20	16	20	20	18	19	20	20	20	18	20	20	17	20

Table 5 presents the results of a population of 25 bees and 25 iterations, conducting 15 round of simulations. Comparing Tab. 5 results to the Tab. 4, all frequency range selected has a vector of 41 points. Also, a result of a model with 25 ants and 25 iterations converge to the middle point at 65 in all simulations conducted.

Table 5. Simulations performed with the BCO to compare the optimal point with the population of 25 bees and 25 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Range	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 6 illustrates the results for a population of 50 bees and 50 iterations, in a total of 15 simulations. In all of them, the selected frequency range has a vector of 41 points. Increasing the bee population and iterations to 50, the result converges again to the middle point 65 in all simulations conducted.

Table 6. Simulations performed with the BCO to compare the optimal point with the population of 50 bees and 50 iterations.

Simulation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Middle Point	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Range	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

With this method is possible to identify that the use of few bees and iterations, the result has low precision. With 25 bees and 25 iterations it is possible to reach the best point and obtain the best frequency range to see the difference between the signatures. The best frequency range to be monitored, which represents the greater difference between the signatures, has 65 as the middle point and a frequency range of 41 points, i.e., representing the 51320-52520 Hz. Figure 6 shows the frequency range optimized by the BCO.

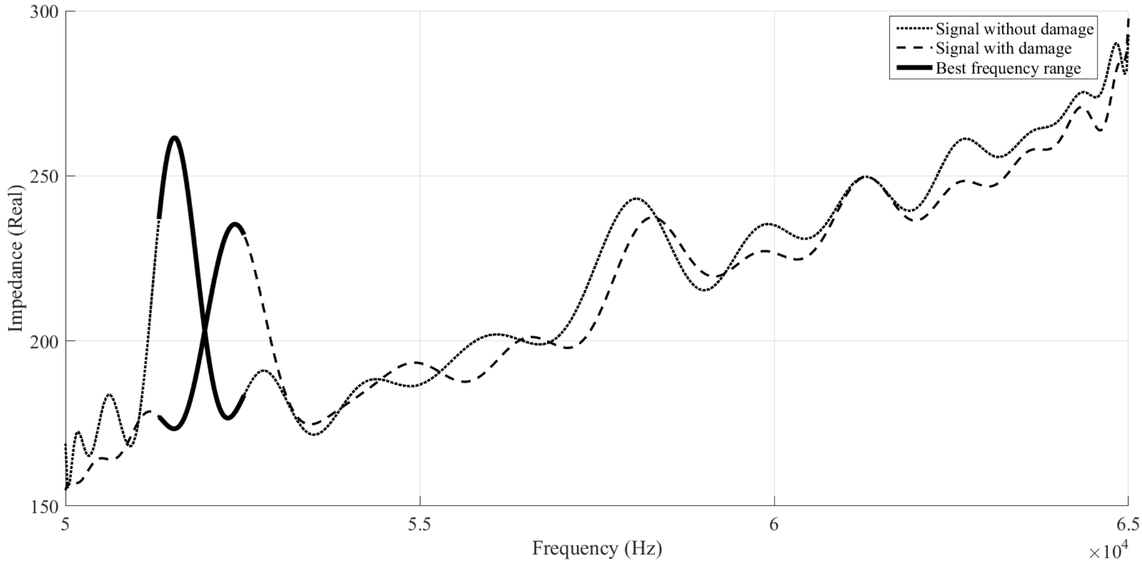

Figure 6. Frequency range optimized by BCO.

According to both frequency ranges in Figures 5 and 6, it can be concluded that both ACO and BCO found similar regions in the frequency to be used for monitoring purposes.

4. CONCLUSIONS

This contribution presented two alternative bioinspired approaches to find the best frequency range of a case study for impedance-based structural health monitoring. Finding the best frequency range can be avoided to compare damaged and baseline signatures in a long range hiding significant features of the damage on the signature.

By the use of the damage metric and both optimization methods, it was possible to check that BCO as well as ACO, considering a population of 25 (bees/ants) and 50 (bees/ants) with 25 and 50 iterations, identified the same optimal or sensitive frequency range to be monitored and can be used for SHM purposes.

5. ACKNOWLEDGEMENTS

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