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CUCKOO SEARCH ALGORITHM FOR OPTIMIZATION OF THE FREQUENCY RANGE IN THE IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

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Abstract. *In several industries it is very common the use of pipeline systems to convey fluid from one location to another. The impedance-based structural health monitoring is a method to supervise and detect premature failures in systems or structures. The aim of this contribution is to identify the best frequency range in a pipeline system in order to be more sensitive to the damages in the monitoring. The optimization method used was the Cuckoo Search Algorithm and the objective function used in this study was the Root-Mean-Square Deviation Damage Metric (M_{RMSD}). It was compared the pristine structure (baseline signature) to the damaged structure (damage signature) in a wide frequency range in order to perform the optimization and check the best range which both curves generated the most different Damage Metric. Concluding, the experiments performed in this case illustrates the optimization method converged to the most different frequency range part of the full signatures, considering both states. Thus, in the next step this best frequency range of the pipeline system will be used to implement an online monitoring system.*

Keywords: *Cuckoo Search Algorithm, Frequency range optimization, Structural Health Monitoring.*

1. INTRODUCTION

Pipeline system is the best fluid transfer method for long distances, presenting lower cost, safety and lower risks of accidents compared to road, rail or sea transports. Damage detection of pipeline structures has a very important role in the industry once can cross-cities and non-urban areas. In addition, many transported products are costly and harmful to environment, requiring safer and well-monitored pipelines to prevent leaks and ruptures, avoiding possible environmental disasters, economic losses, and especially avoiding risks to people (Pita Ruiz, 2014, Du et al. All, 2017, Hong et al., 2013).

In the past five decades new materials have been developed to be used as sensors and actuators in order to be embedded or bonded onto structures. These new components are called Smart Materials and systems that make use of them are named Smart Structures or Smart Systems (Moura Jr and Steffen Jr, 2016, Bento, 2018).

One of the most preeminent technologies are based on piezoelectric materials and bonded to structures in order to measure the electromechanical impedance to take continuous monitoring. The sensor-actuator of these systems use small piezoelectric patches in several places because the method focuses on higher frequency ranges to be able to check very small defects or structure changes (Moura Jr and Steffen Jr, 2016, Bento, 2018). The piezoelectric patches are ceramic components and can be observed in the Fig. 1.

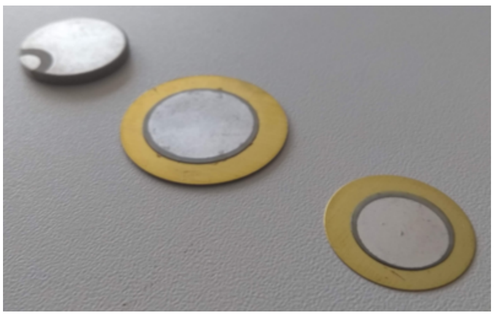

Figure 1. Different types of piezoelectric patches.

The impedance-based structural health monitoring (SHM) is defined as non destructive, easy to implement and monitor and has low cost when compared to other methods. For these reasons, the method is suitable for monitoring structures in hard and costly access locations, such as structures framed in marbles, ducts, ships, submarines, due to their weight and ease of being connected to the structure. is more commonly used in aerospace applications (Moura Jr and Steffen Jr, 2016, Palomino et al., 2012).

The impedance of a mechanical system is represented as the quotient between the force applied to the mechanical system and the resulting alternating linear velocity in the direction of force and at the point applied. It is represented by eq. (1).

$$Z_m = \frac{F}{X(t)} \tag{1}$$

where Z_m is the mechanical impedance, F is the applied force, and $X(t)$ is the velocity. It means a complex magnitude that represents how much a given structure resists to the movement of a force applied on it.

In the impedance-based SHM, the impedance measured is an electromechanical variable due to the coupling between the mechanical structure and the piezoelectric patch. The measurement device excites the PZT (piezoelectric) patch and it will promote the motion on the bonded structure. As effect, the vibration of the structure will strain the PZT patch back. Then, the quotient of the difference of potential (in Volts) applied initially by the current measured in the same PZT patch is the electromechanical impedance of both. The measured impedance signature has two parts: imaginary part that represents capacitive changes of the PZT patch and the real part associated to the structural mechanical resistance, i.e., due to the PZT patch induced vibration. Thus, according to the method, the real part of the impedance signature obtained by the experiment can be related to the integrity of the monitored structure. However, these data measured should be treated in order to obtain quantitative information about the damage in the structure. Sun et al. (1995) proposed one of the most used metrics for this treatment, the mean square root deviation (M_{RSMD})) denoted by Eq. (2).

$$M_{RSMD} = \sum_{i=1}^{n} \frac{\left[Re(Z_{1,i}) - Re(Z_{2,i})\right]^2}{\left[Re(Z_{1,i})^2\right]} \tag{2}$$

where M_{RSMD} is the damage metric, $Z_{1,i}$ is the PZT patch impedance measurement without damage, $Z_{2,i}$ is the PZT patch impedance measurement with damage, i represents the step in the frequency and n is the total of points to be evaluated (size of the signature). Then, Eq.(2) is a quantitative way to evaluate any structure due to damages, having greater damage metrics related to greater damages.

This research intends to optimize the frequency of acquired impedance signals in the use of Cuckoo Search Algorithm in order to detect a greater capacity of detection and identification of damages in the monitored structure. The objective function used in the optimization was the damage metric defined by Eq. (2), once it is a metric very applied in this subject. This metric is responsible to make quantitative analysis of the method, in order to find the greater region of difference between the signatures (baseline and damage cases).

2. CUCO SEARCH ALGORITHM

Heuristics means discover and comes from the Greek word heuriskein. Nowadays, this expression is used to describe a method that is based on perception or experience, conducting to a good solution for specific problem, even not assuring the best one (Foulds, 2012). Metaheuristics are solution methods with small changes of general Heuristics, focusing on more specifically in some problems (Foulds, 2012).

Bioinspired algorithms are some metaheuristic methods based on animal grouping behavior as well as biological phenomenon (Castro and Zuben, 2005).

The Cuckoo Search Algorithm was proposed by Yang and Deb (2009) and benchmarked to Particle Swarm an Genetic Algorithms obtaining better results in some optimization problems. The cuckoo has an aggressive strategy of reproduction. Some species lay their eggs in other nests, even removing eggs from another birds to increase the probability of birth of its own eggs. Some species uses the compulsory breeding parasites by placing their eggs in the nests of other host birds.

Some host birds may come into direct conflict with intruding cuckoos. If a host bird discovers that eggs are not theirs, they will throw those eggs out of the nest or simply abandon their nest and thus build a new nest. Some cuckoo species have evolved in such a way that female parasitic cuckoos are often very specialized in adapting the color and pattern of eggs of selected host species. This reduces the likelihood of your eggs being abandoned and thus increases their reproduction. In addition, studies also show that a cuckoo puppy can also mimic the call of host pups to gain access to more feeding opportunities (Yang and Deb, 2010).

According to Yang and Deb (2009) the algorithm follows the three conditions:

- Each bird lay an egg each time, where the nest is chosen randomly. The prior egg is substituted by new one through a random walk (Levy Flight) applied to the previous egg;
- The best nests goes to the next generation, ensuring the convergence of the solution by the elitism;
- The quantity of host nests are fixed while the layed egg is discovered by the host bird with a probability of p_a.

The pseudo-code of the Cuckoo Search Algorithm is presented in Tab. (1).

Table 1. Pseudo-code of the Cuckoo Search Algorithm

Generate initial population of n host nests (x_i, $i=1, 2, 3, \ldots, n$)
While stop criteria **do**
Find random cuckoo (Levi's flight)
Evaluate objective function f_i
Find random nest j
If $f_i > f_j$ **then**
Exchange j by new solution
End if
Leave a p_a fraction of worst nests and build new ones
Keep best solutions
Rank best solutions and find the best one
End While

According to the algorithm in Tab. (1) the final solution is dependent of the number of host nests, stop criteria (convergence criteria or number of iterations), and the fraction p_a.

3. EXPERIMENTAL PROCEDURE

The pipeline structure of the applied experiment is a *Polyvinyl chloride* (PVC) type of 57 mm of length. The short hydraulic system is composed by a pump, tank, filter, valves and pipes according to the Fig. (1).

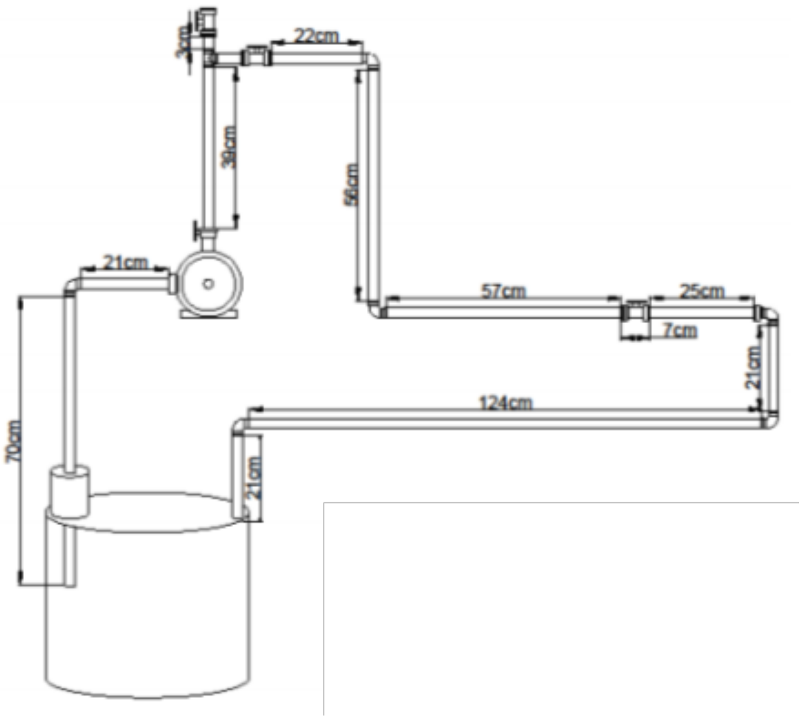

Figure 1. Hydraulic system used in the experiment.

First, it was monitored the baseline signature (pristine condition) and then it was inserted a fixed mass close to the sensor in order to simulate the damage. Figure 2a) and b) illustrates the system and the added mass respectively.

a) Pipeline system b) PZT patch and added mass (damage)

Figure 2. pictures of the pipeline structure and the PZT patch with the simulated damage.

In order to take the measurements of the pipeline, it was developed a plastic structure to bond the piezoelectric patch and hold to the pipe structure. This structure was 3d designed and printed in PLA (Polylactic Acid) plastic and Fig. 3 shows the complete piece.

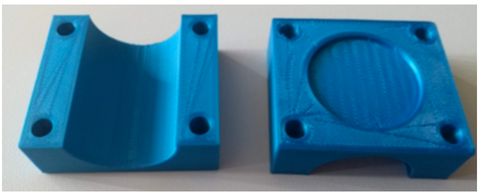

Figure 3. Piezoelectric holder for the pipeline

For the data acquisition of the impedance-based SHM system it was used the EVAL-AD5933EBZ card (fig. 4). The communication between the card and laptop is made through USB cable and by the use of the AD5933 Evaluation Board Software Rev. B. Then, all real part of impedance signatures was gathered.

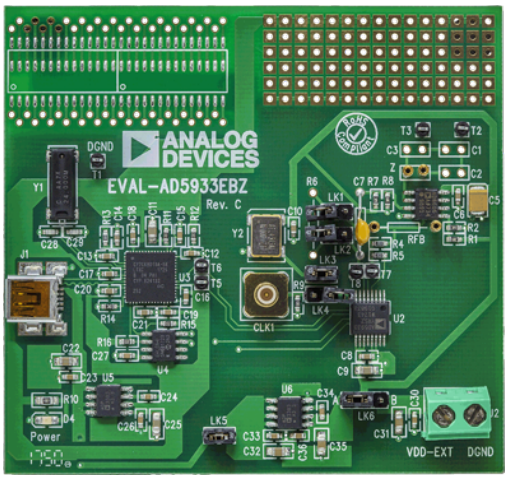

Figure 4. EVAL-AD5933EBZ card

The monitored frequency range was from 20 to 100 KHz, with a step of 156 Hz, and a total of 4096 points. It was measured 10 samples of the non-damaged structure and 10 samples of the damaged structure, and later, an average of each of the frequency range measurements: 20-30 kHz, 30-40 kHz, 40-50 kHz, 50-60 kHz, 60-70 kHz, 70-80 kHz, 80-90 kHz and 90-100 kHz. also, the samples were investigated to check outliers and averaged and the final signature is represented by Fig. 5 (non-damaged and damaged cases).

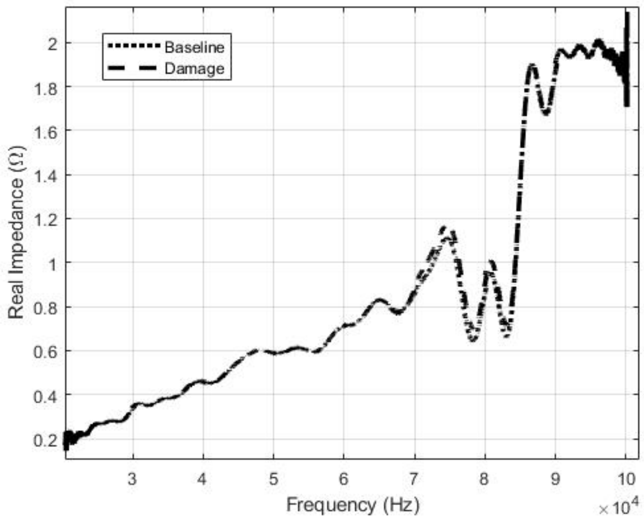

Figure 5. Baseline and damaged signatures (averages).

4. RESULTS AND DISCUSSIONS

It was used only the real part of the impedance signature for the structure with and without damage according to previously described in the introduction section. By the use of the Cuckoo Search algorithm we have the result shown in Fig. 6.

In this case study it was used only the real part of the impedance signatures, for both cases: damaged and damaged conditions. Equation (2) was defined as objective function. Then, 10 simulations were done changing the number of nests and iterations, starting from 10 iterations and 10 nests. The observed result was not satisfactory for this case because each one converged to different optimal points.

Further, considering 20 iterations and 20 nests leads to a better result because only two best points were obtained. For 30 iterations and 30 nests were found four best points and for 40 iterations and 40 nests were found eight. Finally, in the last condition, 50 iterations and 50 nests all conditions converged to the optimal point 3043, corresponding to the frequency range of 75640-83400 Hz, meaning the greatest difference between the pristine and damaged signatures. Thus, the algorithm found the best frequency range and can be used as approach for frequency range optimization. Table 2 illustrates the convergence of the method for the described conditions.

Table 2. Convergence of the Cuckoo Search Algorithm.

Simulation	1	2	3	4	5	6	7	8	9	10	Central Point (vector of data)	Optimized Freq. Range
10 iterations e 10 nests	2999	2950	2855	3038	2881	2995	2721	3111	3097	2791	2943	76640 - 81400 Hz
20 iterations e 20 nests	3043	3051	3033	3038	3045	3035	3038	3043	3045	3036	3040	75580 - 83340 Hz
30 iterations e 30 nests	3043	3043	3041	3042	3043	3043	3041	3042	3039	3046	3042	75620 - 83380 Hz
40 iterations e 40 nests	3043	3042	3043	3042	3043	3043	3043	3043	3043	3043	3042	75620 - 83380 Hz
50 iterations e 50 nests	3043	3043	3043	3043	3043	3043	3043	3043	3043	3043	3043	75640 - 83400 Hz

For a better visualization, Figs. 6 and 7 represent in red (continuous line) the optimized frequency range (75640-83400 Hz) obtained by the Cuckoo Search Algorithm. It was considered 50 iterations and 50 nests for the optimization of the impedance signatures, having as the central point of the frequency range the 3043 of the vector of the measurement.

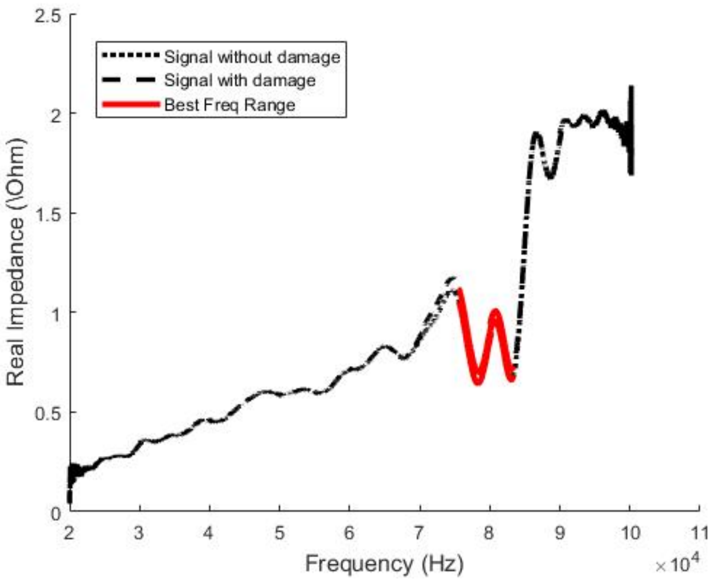

Figure 6. Complete signature of the structure

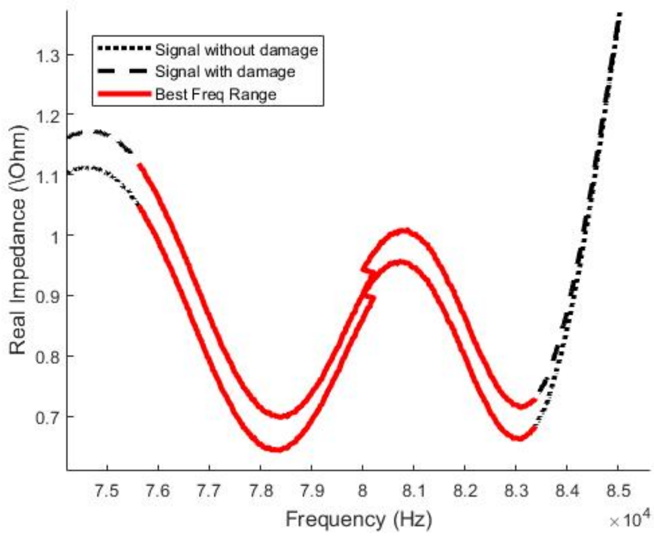

Figure 7. Zoom of the best frequency range

It can be observed by Fig. 6 and Fig. 7 the possibility of using frequency range optimization using the Cuckoo Search Algorithm which illustrates the region of the signatures with major difference. Then, it is possible to find the range with the greatest divergence between the structure without and with the damage, allowing the identification of the damage in the pipe structure.

5. CONCLUSION

It was evaluated a tubulation structure in order to verify possible impedance signature changes simulating mechanical damages. Thus, it was used the damage metric M_{RSMD} as objective function and the Cuckoo Search Algorithm in order to find the best frequency range able to monitor the system due to the maximum difference between pristine and damaged signatures.

The best frequency range obtained by the optimization method converges to 75640-83400 Hz, illustrating the greatest difference between damaged and undamaged signatures. Thus, the Cuckoo Search Algorithm represents a good approach to find the best frequency range considering the easier implementation compared to more sophisticated methods as well as fast result return.

An additional contribution was the development of the support structure to bond the piezoelectric patch in order to allow the reuse of the sensor in different places of the pipeline. Concluding, after the frequency range was optimized for the damage identification of the pipeline system, a next contribution will be conducted in the same structure to investigate corrosion and clogging conditions. Further works would investigate real conditions of pipelines in industrial uses.

6. ACKNOWLEDGMENTS

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