Structural damage detection using the Circle-Inspired Optimization Algorithm

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Abstract. This paper presents a novelty approach to vibration-based damage detection using matrix updating with the Circle-Inspired Optimization Algorithm (CIOA). The methodology is evaluated through numerical simulations of three structures: a 10-bar truss, a cantilever beam, and a Warren truss. In all cases, the systems are subject to ambient vibrations with varying noise levels to replicate inaccuracies in the acceleration signals. Furthermore, different analysis scenarios were considered, including single and multiple damages. The Data-driven Stochastic Subspace Identification (SSI-DATA) technique is employed to determine the modal parameters of these signals. Natural frequencies and mode shapes are compared under healthy and damaged conditions to identify the damage state through the methodology. Considering all analyses for each scenario, the highest percentage errors in damage detection obtained were 0.163% in a multiple damage scenario with noise of 3% for the 10-bar truss, 1.453% in a multiple damage scenario with 5% noise for the cantilever beam, 3.600% in a multi damage scenario with 5% noise for the warren truss. Therefore, results demonstrate the proposed approach's promise in identifying, locating, and quantifying single and multiple damages.

Keywords: Damage Detection, Circle-Inspired Optimization Algorithm, Structural Health Monitoring.

1 Introduction

Structural Health Monitoring (SHM) plays a crucial role by providing continuous monitoring to ensure user safety. SHM techniques primarily rely on analyzing the structure's vibration responses over time. These methods assess structural health by examining damage-sensitive indicators like natural frequencies and mode shapes. Each damage detection methodology has distinct limitations, reinforcing the necessity of testing, comparing, and refining damage detection strategies across various civil structures to ensure their efficiency and effectiveness. Most methods utilize changes in damage-sensitive features to evaluate structural health, including modifications in modal parameters [1-3], derivatives of these parameters [4-5], modal flexibility approaches [6-7], Bayesian probabilistic inference [8-9], wavelet transforms [10-11], matrix updating [12-14], and Machine Learning techniques [15-16].

Optimization-based or matrix updating methods modify the system's matrices (stiffness and damping) to accurately mirror the measured dynamic or static responses on Finite Element (FE) models. The optimization process involves solving equations of motion with experimental data and comparing the original and updated matrices to identify damage. Due to the ill-posed nature of this problem, gradient-based optimization methods are often inadequate, prompting the use of Metaheuristic algorithms to manage complex objective functions [17-18].

Within this framework, this paper introduces a novel approach for detecting, locating, and quantifying structural damage using modal parameters derived from ambient vibrations. Unlike many existing studies, this research utilizes the Circle-Inspired Optimization Algorithm (CIOA), a new algorithm developed by de Souza and Miguel [19]. The methodology is validated using three numerical models: a 10-bar truss, a cantilever beam, and a Warren truss footbridge, all subjected to environmental vibrations and noise. The structure of the paper is as follows: Section 2 details the damage detection method based on CIOA matrix updating, Section 3 presents three numerical examples, and Section 4 concludes the study.

2 Optimization-based damage detection method

Methods for damage detection based on optimization solve a problem where the objective function uses modal parameters as variables. It necessitates a finite element (FE) model that aligns with the structure under examination, aiming to match the experimental data collected. The primary aim here is to reduce discrepancies between the parameters observed in the actual structure and those predicted by the model.

In this paper, damage identification, localization, and quantification were approached by viewing damage as modifications in stiffness values. To achieve this, a stiffness reduction coefficient, denoted as α_i , was introduced. This coefficient varies between 0 and 1, with 1 representing undamaged conditions and 0 indicating total stiffness loss in element *i*. Consequently, α_i influences the stiffness matrix $\mathbf{k}_i$ of every individual element across the entire N_e elements within the structure:

$$\mathbf{K} = \sum_{i=1}^{N_e} \alpha_i \mathbf{k}_i \, , \tag{1}$$

where $\mathbf{K}$ is the global stiffness matrix. Estimating structural damage involves iteratively refining a numerical model through adjustments across all α_i coefficients. These updates continue until the discrepancy between the model predictions and experimental data is minimal. The optimization task is framed as a minimization issue characterized by an objective function ($\Pi(\alpha)$) based on the experimental modal feature extracted from the structure E , and the analytical modal feature calculated from the structure's FE model $A(\alpha)$. Equation (2) presents the optimization task and the objective function, which was also used by Fadel Miguel et al. [12] and Fadel Miguel et al. [13]. This equation is based on the natural frequencies and mode shapes obtained analytically and experimentally:

$$\text{Find } \alpha$$

$$\text{Minimize } \Pi(\alpha) = \left|E - A(\alpha)\right|^2 = \sum_{j=1}^{N_m}\left[\left(\frac{\delta\omega_i(\alpha)}{\omega_i}\right)^A - \left(\frac{\delta\omega_i}{\omega_i}\right)^E\right]^2 + \sum_{j=1}^{N_m}\sum_{k=1}^{N_n}\left[\left(\delta\psi_{ki}(\alpha)\right)^A - \left(\delta\psi_{ki}\right)^E\right]^2 \, , \tag{2}$$

$$\text{Subject to } 0 \le \alpha \le 1$$

where N_m is the number of analyzed vibration modes, N_n is the number of nodal displacements, the superscripts *A* and *E* represent analytical and experimental, respectively, ω_i are the natural frequencies for the i^{th} mode of the healthy condition for both experimental and analytical conditions, $\delta\omega_i$ is a fractional change of experimental and analytical natural frequencies for the i^{th} mode of the structure, and $\delta\psi_{ki}$ is a fractional change of experimental and analytical mode shapes for the i^{th} mode of the structure.

The next section summarizes the Circle-Inspired Optimization Algorithm (CIOA), the algorithm used to solve the minimization problem proposed in this work.

2.1 Circle-Inspired Optimization Algorithm

The Circle-Inspired Optimization Algorithm (CIOA) is an efficient metaheuristic optimization algorithm developed by the authors [19], in which search agents perform movements inspired by circle arcs. These movements are governed by two main parameters: a user-defined angle θ and a radius r calculated by the algorithm. In addition to the angle θ, the user must enter a parameter $Glob_{it}$ between 0 and 1, representing the proportion of global search iterations, before the algorithm performs a local search.

In the main loop, after the first iteration, which is random, in any iteration *k*, the research agents will be classified according to the solution obtained and, in this way, the agent that produced the j^{th} best solution will have its coordinates updated in iteration k + 1according to:

$$x_{2i}(k+1) = x_{2i}(k) - rand_1 r_j \sin(k\theta) + rand_2 r_j \sin((k+1)\theta), \quad (3)$$

$$x_{2i-1}(k+1) = x_{2i-1}(k) - rand_3 r_j \cos(k\theta) + rand_4 r_j \cos((k+1)\theta), \quad (4)$$

where k represents the current iteration, θ is the user-defined angle, $rand$ are random numbers drawn from a uniform distribution between zero and one, $2i$ and $2i-1$ refer to even and odd numbers respectively, and r_j is the j^{th} element of a vector of radius. This radius vector $\vec{r}$ is constructed by Equation (5), in which N_{ag} is the number of search agents, L_b and U_b are the lower and upper limits of design variables, and c_r is an auxiliary variable.

$$r_j = \frac{c_r j}{N_{ag}}, \quad 1 \le j \le N_{ag} \quad \text{and} \quad c_r = \frac{\sqrt{U_b - L_b}}{N_{ag}}. \quad (5)$$

Whenever $k\theta$ exceeds a multiple of 360°, the radius vector is updated to improve the algorithm's convergence:

$$\vec{r}_{new} = \vec{r}.r_{up}, \quad (6)$$

where $\vec{r}$ and $\vec{r}_{new}$ represent the radius vector before and after the update, respectively. r_{up} is an update coefficient generally defined with values close to, but not equal to, 1. In this work, r_{up} = 0.98 was used.

The local search starts at iteration k, when the ratio k/N_{it} equals $Glob_{it}$, where N_{it} is the total number of iterations. At this point, all search agents have their design variables updated to the values that produced the best solution so far. Furthermore, the lower and upper boundaries of design variables are updated according to Equations (7), in which L_{b1_i} and U_{b1_i} are the new lower and upper bounds, and $x_{i_{best}}$ is the variable in dimension i that has produced the best solution so far.

$$L_{b1_i} = x_{i_{best}} - \frac{U_b - L_b}{10000} \quad \text{and} \quad U_{b1_i} = x_{i_{best}} + \frac{U_b - L_b}{10000} \quad (7)$$

After initialization, the local search is governed by the same Equations described previously, i.e., Equations (3) to (6). Furthermore, the CIOA algorithm presents rules to prevent search agents from exceeding design variables' lower and upper boundaries, which can be seen in detail in [19]. Regarding the algorithm parameters that the user must define, it is recommended that the angle θ be defined as a non-divisor value of 360, and that $Glob_{it}$ assumes values between 0.75 and 0.95. The complete CIOA code in MATLAB can be obtained through the link: https://github.com/oapsouza/CIOA-Circle-Inspired-Optimization-Algorithm-Matlab-version.

3 Numerical examples

In this section, the Circle-Inspired Optimization Algorithm was used as a damage detection method to numerically simulate experimental tests of three structures: a 10-bar truss, a cantilever beam, and a Warren truss. All codes were developed in MATLAB; the CIOA parameters are θ = 97º and $Glob_{it}$ = 0.90.

3.1 10-bar truss

The first structure analyzed in this paper consists of a 10-bar truss (Begambre and Laier [20]), as shown in Fig. 1. The structure elements have a specific mass of 7700 kg/m³, Young's modulus of 195 GPa, moment of inertia of 3×10^{-8} m^4 and cross-section of 4.2×10^{-4} m^2. The arbitrated damping ratio for the 1st and 3rd vibration modes was 1%.

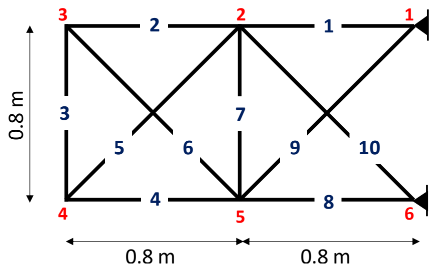

Figure 1. 10-bar truss

An analysis was carried out for the scenario of 15% stiffness reduction in bars 2 and 8 simultaneously, using 3% noise in the response signals of the intact and damaged scenarios. The damage detection obtained by CIOA on the 10-bar truss with 100 search agents and 300 iterations is presented in Tab. 1.

Table 1. Results of the damage detection for the 10-bar truss structure

Bar	Exact damage	Begambre and Laier [20]	Fadel Miguel et al. [12]	Monteiro et al. [16]	CIOA
1	1	1	0.9995	0.9974	1
2	**0.85**	**0.8476**	**0.8537**	**0.8544**	**0.852**
3	1	0.9987	1	1.0447	0.999
4	1	0.9862	0.9998	1.0087	0.998
5	1	0.9829	0.9946	1.0115	1
6	1	0.9992	1	1	0.999
7	1	1	1	1.0165	1
8	**0.85**	**0.8503**	**0.8500**	**0.8460**	**0.851**
9	1	0.9996	1	0.9977	1
10	1	1	1	1.0094	1

The CIOA performed satisfactorily in detecting damage in bars with stiffness reduction: bars 2 and 8. In undamaged elements, the highest error occurred in bar 4. CIOA obtained a stiffness reduction coefficient of approximately 0.998, corresponding to an error of 0.163%. In addition, the solutions obtained by Begambre and Laier [20], Fadel Miguel et al. [12], and Monteiro et al. [16] demonstrate the CIOA's efficiency in detecting damage in this problem.

3.2 Cantilever beam

The second structure studied in this paper is a metal beam with a square cross-section box type with an external dimension of 25.4 mm and a thickness of 1 mm. The length of the structure is 750 mm, and 25 Timoshenko beam elements were used for modeling, as shown in Fig. 2. The structure has a specific mass of 28 kg/m³, a Young's modulus of 68.6 GPa, a Poisson coefficient of 0.3, and a Timoshenko shear coefficient of 0.5. A concentrated mass of 18.2 g was added in all degrees of freedom. The arbitrated damping ratio for the 1*st* and 5*th* vibration modes was 1%.

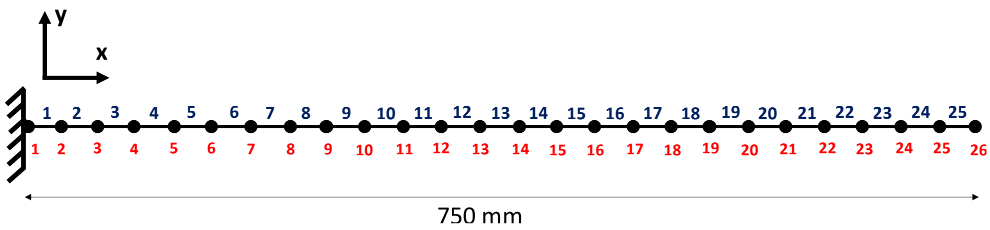

Figure 2. Cantilever beam with 25 elements

Three damage scenarios were evaluated, considering a 5% noise level in the acceleration signals for each scenario. In scenario 1, there is a 20% reduction in stiffness in element 20. In scenario 2, element 8 shows a 30% reduction in stiffness. In scenario 3, elements 5 and 12 show a 50% and 30% reduction in stiffness, respectively. The damage detection results obtained through CIOA with 250 search agents and 400 iterations are presented in Fig. 3, in which it is observed that the algorithm was very efficient, detecting damage to the correct bars in all scenarios considered. Furthermore, the CIOA had better overall performance in damage detection than the results presented by Miguel et al. [13] and Zeni [21].

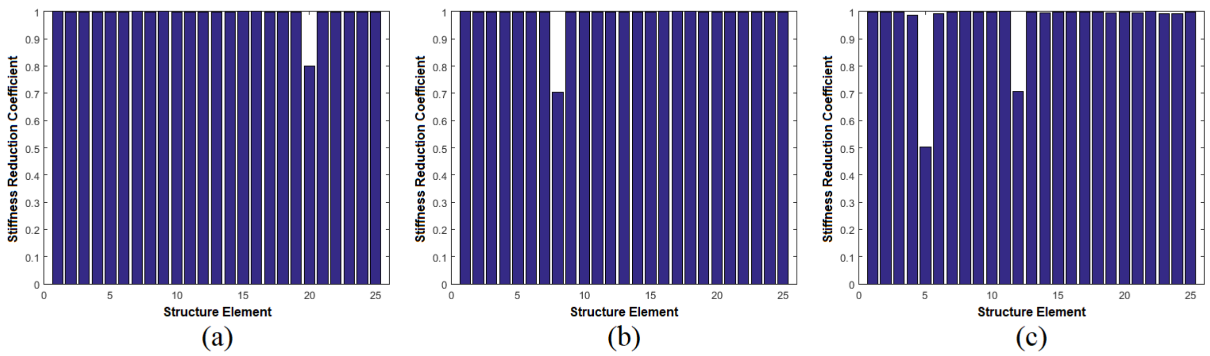

Figure 3. Damage results for the cantilever beam: (a) scenario 1, (b) scenario 2, (c) scenario 3

The stiffness reduction coefficients for the damaged elements are presented numerically in Tab. 2, where they are compared with the exact value. Notably, the values obtained by CIOA are very similar to the exact ones, and the most significant error in damaged elements was only 0.606%.

Table 2. Stiffness reduction coefficients for the cantilever beam estimated through CIOA

Scenario	Element	Exact damage	CIOA damage	Error (%)
1	20	0.8	0.799	0.111
2	8	0.7	0.704	0.391
3	5	0.5	0.504	0.354
	12	0.7	0.706	0.606

In the undamaged elements, the highest error found was in element 4, for scenario 3, where CIOA estimated a stiffness reduction coefficient of 0.985, inducing an error of just 1.453% in this element.

3.3 Warren truss

The third and final structure analyzed in this paper is a warren truss footbridge with a span of 39 m and a height of 2.23 m, as illustrated in Fig. 4. The Young's modulus is 200 GPa, the specific mass is 7850 kg/m³, and the damping ratios in the 1st and 5th vibration modes are 1%. The truss bars have varied cross-sections according to their structural function: bars 1 to 13, which are the lower chords, have areas of 0.006 m²; the diagonal bars, which are numbered 14 to 41, have areas of 0.004 m²; and the upper chords bars numbered from 42 to 55 have areas of 0.008 m².

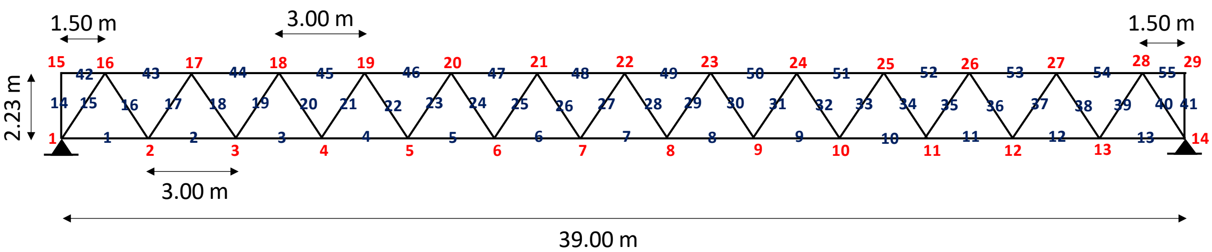

Figure 4. Warren truss footbridge with 55 bars

Five damaged scenarios were analyzed, with different intensities and positions of the damaged bars. The scenarios also include single and multiple damages, as described below: Scenario 1 presents bar 7 with a 20% reduction in stiffness. Scenario 2 presents bar 54 with a 20% reduction in stiffness. Scenario 3 presents bars 26 and 27 with 30% and 20% reduction in stiffness, respectively. Scenario 4 presents bars 5 and 46 with 30% and 20% reduction in stiffness, respectively. Scenario 5 presents bars 7, 45, and 52 with 40%, 30%, and 30% reduction in stiffness. A 5% noise level is considered for acceleration signals in all scenarios. The damage detection results obtained with CIOA using 300 search agents and 800 iterations are presented in Fig. 5.

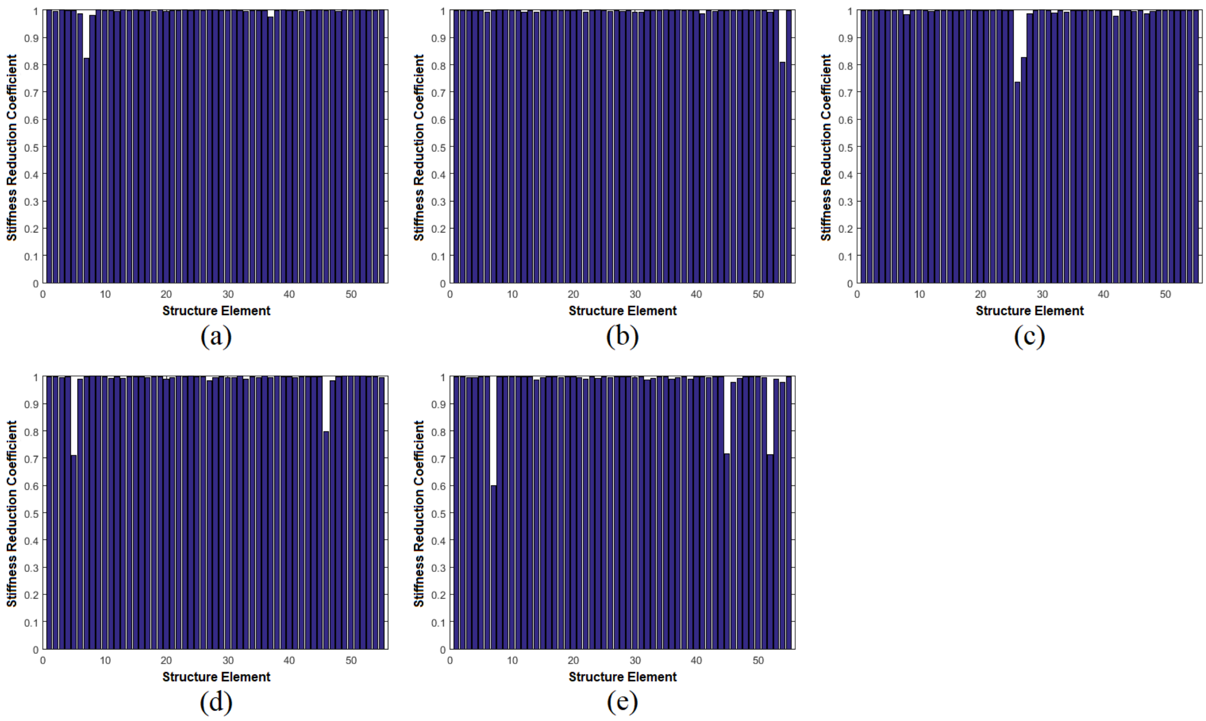

Figure 5. Damage results for the warren truss: (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4, (e) scenario 5

As can be seen in Fig. 5, in all scenarios, the CIOA correctly detected the damaged elements. The stiffness reduction coefficients for the damaged elements are presented numerically in Tab. 3, where they are compared with the exact value. The most significant error, 3.6%, occurred in bar 26 of scenario 3. This is a multiple-damage scenario, where the damaged bars have the same structural function (diagonal bars) and are connected.

Table 3. Stiffness reduction coefficients for the warren truss estimated through CIOA

Scenario	Element	Exact damage	CIOA damage	Error (%)
1	7	0.8	0.824	2.441
2	54	0.8	0.808	0.791
3	26	0.7	0.736	3.600
	27	0.8	0.826	2.612
4	5	0.7	0.709	0.892
	46	0.8	0.798	0.216
5	7	0.6	0.599	0.069
	45	0.7	0.716	1.573
	52	0.7	0.714	1.389

In the undamaged bars, the highest error occurred in bar 37 of scenario 1, where CIOA found a stiffness reduction coefficient of 0.977, inducing an error of 2.349% for this element.

4 Conclusions

In this paper, vibration-based damage detection was performed using matrix updating through the Circle-Inspired Optimization Algorithm (CIOA). Natural frequencies and mode shapes were used as damage-sensitive features to detect, localize, and quantify through a minimization problem considering the experimental and numerical data. The results obtained in the three structures analyzed considering different damage scenarios, in which the highest error obtained was only 3.6% in a multiple damage scenario involving a structure with 55 elements, proved that the proposed methodology is efficient not only in identifying damage but also to estimate its position and extent.

Acknowledgements. The authors acknowledge the financial support of CAPES and CNPq.

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