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NUMERICAL OPTIMIZATION OF STRAIN SENSOR PLACEMENT FOR LOAD MONITORING IN 2D STRUCTURES

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Abstract: *Operational load monitoring is essential for structural health assessment and possible fatigue failure prediction. In such processes strain sensors are usually used to capture localized deformations for precise load estimation. But, the monitoring accuracy depends on placement and orientation of the sensor. This study employed a numerical method to optimize strain sensor placement in 2D structures. The goal is to determine sensor location and orientation in order to capture maximal values of strain in the structure. Objective function was definied and genetic algorithm was implemented to find the global extremum of the function. The developed methodology and algorithms were tested with two structural examples of irregular geometry. In both cases the optimization algorithm converged to optimal sensor position. The results proved that the method can be used to improve measurement accuracy and cost efficiency for operational load monitoring processes.*

Keywords: strain sensor, optimization, genetic algorithm, finite element method

1. Introduction

Operational load monitoring is an essential part of structural health assessment that can be used to evaluate stress distributions and safety in real time and to predict potential fatigue failure (Mucha et al., 2020). Such processes are sensor-based and very often strain sensors provide localized deformation data, which facilitates estimation of external loads and internal stresses (Lu et al., 2018). But, the effectiveness of strain-based monitoring is highly dependent on sensor placement (Li et al., 2022). Therefore, sensor placement optimization is very important to enhance the strain measurement sensitivity (Di Nuzzo et al., 2021).

This study focused on optimizing strain sensor placement in 2D structures to maximize measured values. It is assumed that in the load monitoring processes, the relation between load value and measured strain in known and, in case of linear-elastic materials, proportional. Therefore, maximization of measured values increases accuracy of measurements, and could allow the use of lower-resolution hardware without sacrificing reliability. In this study, a numerical approach was used which integrated a genetic algorithm (GA) for optimization with finite element method (FEM) for structural analysis. GA is a bio-inspired algorithm that is well-suited to solve structural optimization problems due to its ability to efficiently explore large design spaces and converge toward global extremum in cases where the objective function values are calculated from results of a finite element model (Burczyński et al., 2020).

2. Optimization problem

Let us consider a 2D structure $\mathbf{\Omega}$ of boundary $\mathbf{\Gamma}$, placed in x-y global coordinate system, presented in Fig. 1. The structure boundary is partially supported by known displacements $\mathbf{u_0}$ and loaded by forces $\mathbf{f_0}$. The load value is monitored with a strain sensor **S** of dimensions b x h placed with its middle point $\mathbf{P_S}$ in coordinates (x_s, y_s). The sensor edges are parallel to a local coordinate system ξ-η which is inclined to the global x-y axes at the angle of φ_s. The relation between load $\mathbf{f_0}$ and strain measurement ε_s is known and proportional in case of linear-static material.

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Because the sensor dimensions b and h are relatively small compared to the dimensions of the structure $\mathbf{\Omega}$, ε_s can be approximated as the average of strain measurements at points $\mathbf{P}_1$ and $\mathbf{P}_2$:

$$\varepsilon_s \approx 0.5\left(\varepsilon_s^{P_1} + \varepsilon_s^{P_2}\right). \tag{1}$$

The measured strain value at point $\mathbf{P}_i$ can be expressed as

$$\varepsilon_s^{P_i} = \varepsilon_\xi^{P_i} + \alpha\varepsilon_\eta^{P_i} \tag{2}$$

where ε_ξ^{Pi} and ε_η^{Pi} represent parallel and perpendicular strain components to the sensor orientation at point $\mathbf{P}_i$ and α is a sensitivity coefficient.

Strain components in the local coordinate system ξ-η can be calculated by rotating the strain tensor expressed in global coordinates x-y by the angle of φ_s:

$$\begin{bmatrix} \varepsilon_\xi & \varepsilon_{\xi\eta} \\ \varepsilon_{\xi\eta} & \varepsilon_\eta \end{bmatrix} = \begin{bmatrix} \cos\varphi_s & \sin\varphi_s \\ -\sin\varphi_s & \cos\varphi_s \end{bmatrix} \begin{bmatrix} \varepsilon_x & \varepsilon_{xy} \\ \varepsilon_{xy} & \varepsilon_y \end{bmatrix} \begin{bmatrix} \cos\varphi_s & -\sin\varphi_s \\ \sin\varphi_s & \cos\varphi_s \end{bmatrix}. \tag{3}$$

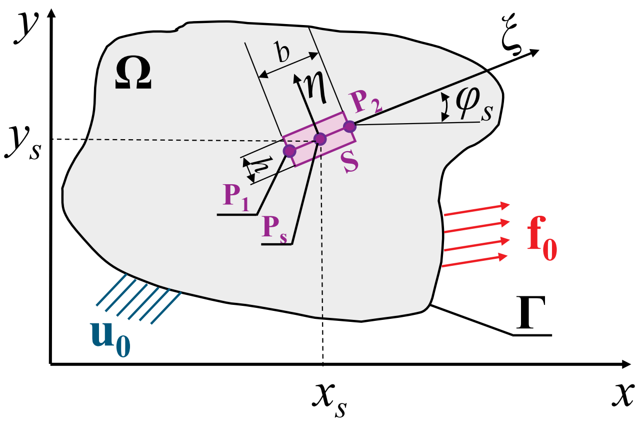

Fig. 1: Sensor placement problem.

The considered problem is to find the optimal values of sensor coordinates and orientation (x_s, y_s, φ_s) for which the strain measurement value ε_{meas} is maximal. Therefore, the optimization problem can be expressed as maximization of the objective function: max(f), where f is expressed as follows:

$$f(x_s, y_s, \varphi_s) = \begin{cases} 0 & \text{, if sensor partially/entirely outside of } \mathbf{\Gamma} \\ \text{abs}(\varepsilon_s) & \text{, if sensor inside of } \mathbf{\Gamma} \end{cases}. \tag{4}$$

Design variables x_s and y_s are limited to the minimal and maximal coordinates values of the structure $\mathbf{\Omega}$. Third design variable φ_s is limited to the range [0, 180°].

3. Numerical examples

Two structures with irregular boundaries, in plane stress, presented in Fig. 2, are considered as numerical examples. The material for both cases is structural steel (with Young's modulus of 205 GPa and Poisson's ratio of 0.3). Finite element models of the structures were created in ANSYS Workbench software. Structure 1 is a plate of overall dimensions of 30 x 90 x 3 mm. It is fixed on the bottom edge and in tension by the load applied uniformly on the top edge. Structure 2 is a bell crank of overall dimensions of 300 x 300 x 5 mm. Load and supports of the structure 2 in the finite element model were applied to the holes edges using MPC constraints. Structure 2 is simply supported (allowing rotation) in its bottom left hole and loaded in its bottom right hole by a vertical force. The translation of vertical load to horizontal load is simulated using a spring mounted to the top hole, as presented in the figure. Topology optimization of structure 2 (excluding holes edges) was performed with the objective of compliance minimization and constraint to retain 20% of the initial mass. Based on the topology optimization results, final geometry was designed.

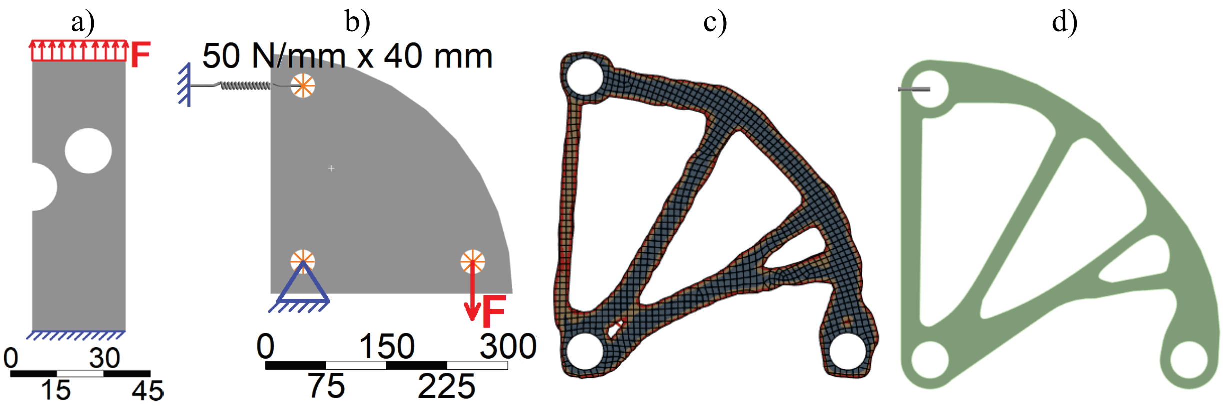

Fig. 2: Geometry and boundary conditions: a) geometry and boundary conditions of structure 1 (scale in mm), b) initial geometry and boundary conditions of structure 2 (scale in mm), c) results of topology optimization of structure 2, d) final geometry of structure 2.

3.1. Optimization parameters

It was assumed that the dimensions of the sensor were b = 5 mm, h = 2 mm, and the sensitivity coefficient was α = 0.1. Additional constraint was assumed – that the sensor should not be placed closer than 2 mm from the boundary $\mathbf{\Gamma}$.

To solve the optimization problem, genetic algorithm implemented in the *Global Optimization Toolbox* of the MATLAB software was utilized. Nodal strain data from ANSYS software was imported. Strain results, for example load value of F = 100 N for both structures, are shown in Fig. 3.

The population size was set to 200. Because the boundaries of the example structures (especially structure 2) are highly irregular, a custom function for generating the initial population was implemented to improve convergence process. All the individuals of the initial population were chosen randomly with uniform probability with the rule that for every individual the sensor must entirely fit within the structural boundaries (have nonzero objective function value). Other parameters of the genetic algorithm were left as default.

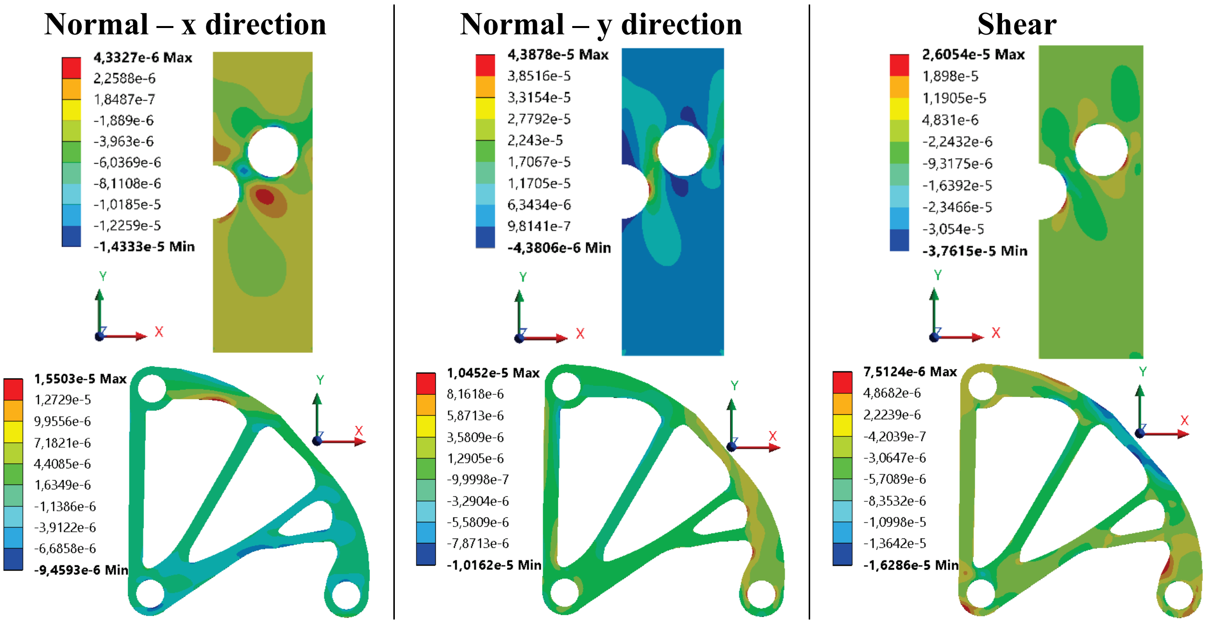

Fig. 3: Strain distribution maps, in mm/mm.

3.2. Optimization results

For both cases the genetic algorithm stopped because of low average change in the objective function value, for structure 1 after 262 generations with the best objective function value of 17.85 µm/m, and for structure 2 after 107 generations with the result of -14.39. Convergence plots are presented in Fig. 4. The optimal solution for structure 1 was: x_s = 10.80 mm, y_s = 49.54 mm, φ_s = 110.01°. The optimal solution for structure 2 was: x_s = 203.95 mm, y_s = 190.23 mm, φ_s = 133.44°. Optimal sensor placements are presented in Fig. 5.

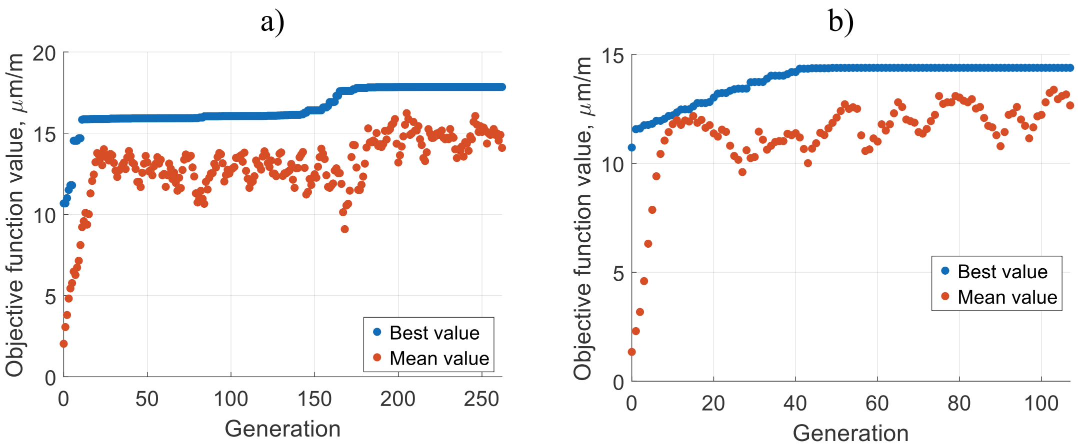

Fig. 4: Plot of objective function value over generations: a) for structure 1, b) for structure 2

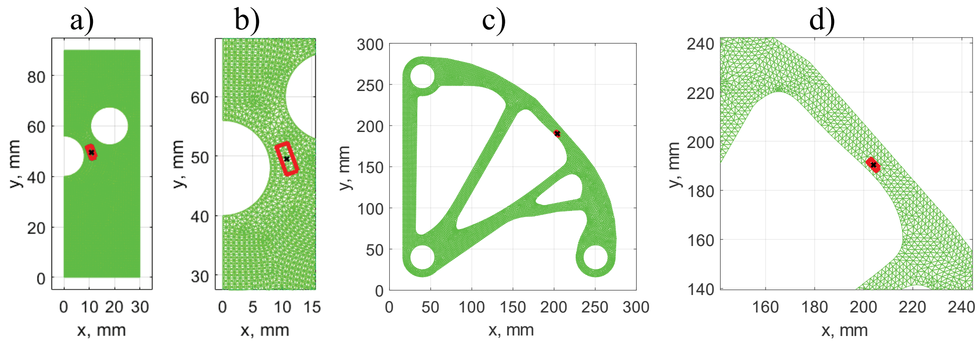

Fig. 5: Visualization of optimal solution: a) for structure 1, b) for structure 1 – closeup, c) for structure 2, d) for structure 2 – closeup

4. Conclusions

This study presented numerical optimization procedure for strain sensor placement in 2D structures. For several runs of the genetic algorithm (for both considered cases) every time similar results were obtained. This means that in both examples the genetic algorithm converged to optimal sensor position. In the testing phase, such convergence was achieved by setting relatively high population size and implementing custom function for generating the initial population. The results proved that the presented method can be used to improve measurement accuracy and cost efficiency for operational load monitoring processes as higher measurement values may allow the use of lower-resolution data acqusition system than for non-optimal sensor position. The presented method takes into account the sensor sensitivity to perpendicular stress therefore, the optimal sensor position may be different than the coordinates and direction of maximal strain in the considered structure.

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