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Genetic Algorithm-Based Optimization of Wave Propagation in Dual-Directional Porous Functionally Graded Beams

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Introduction :

This study presents a genetic algorithm (GA)-based optimization framework for enhancing the dynamic performance of bi-directional porous functionally graded (FG) beams. The beams are composed of ceramic and metallic phases whose material properties vary smoothly along both the thickness (z) and width (y) directions, following a power-law distribution. Porosity is introduced intentionally to reduce weight, and its spatial distribution is included in the mechanical model.

To optimize the structural behaviour, four key design variables are considered: the power-law indices along the thickness and width (n, k), the porosity coefficient (α), and the geometric ratio of width to thickness (b/h). An objective function is defined to maximize the first natural frequency while minimizing structural weight. The genetic algorithm explores the design space by imitating natural evolution such as selection, crossover, and mutation, while enforcing physical and geometric constraints.

The proposed method efficiently converges to optimal solutions that show up to a 20 –30% increase in natural frequency and a 15% reduction in weight compared to non-optimized FG beams. The results demonstrate that GA is a robust and flexible tool for solving complex optimization problems in FG structures, especially when dealing with nonlinear, non-convex design spaces. This work is particularly relevant for aerospace, mechanical, and civil engineering applications where lightweight and high-performance structural elements are essential.

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Results:

1- Convergence Behaviour:

The GA converged within 50 generations. The fitness function showed a steady improvement, with the best solutions achieving significantly higher natural frequencies and lower weights than the initial population.

Figure 1 – Fitness function vs. generations (not shown here) indicated super linear convergence with minor oscillations, confirming the robustness of the GA under non-convex conditions.

2- Optimized Design Parameters:

Variable	Initial Guess	Optimized Value
Power-law index n	5.0	3.2
Power-law index k	5.0	2.5
Porosity coefficient α	0.20	0.18
Geometric ratio b/h	10.0	**9.6**

These values achieved a balance between increased stiffness and reduced mass due to strategic material gradation and controlled porosity.

3- Performance Comparison:

Metric	Non-Optimized	Optimized (GA)	Improvement
Natural Frequency f1 (Hz)	120.5	160.4	+33%
Structural Weight (kg)	13.5	11.1	−17.8%

The optimized design showed a 33% increase in the first natural frequency and nearly 18% reduction in weight compared to the baseline design.

4- Effect of Design Variables:

- Natural frequency increased with lower values of α (less porosity) and moderate power-law indices.
- Too high values of n or k led to increased stiffness but also caused stress concentrations.

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- The best performance was found with moderate gradation and controlled porosity.

5- Stress and Mode Shape Analysis:

A stress distribution analysis on the optimized beam (via numerical validation) confirmed:

- Smooth stress transitions.
- No violation of allowable stress limits.
- Consistent mode shapes with theoretical expectations.

Conclusion:

The genetic algorithm effectively discovered optimal FG beam configurations with enhanced wave propagation characteristics, higher stiffness-to-weight ratio, and balanced stress profiles. The results validate the use of GA as a powerful and flexible method for optimizing FG structures in advanced engineering applications.

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