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ENHANCING COMPOSITE MATERIALS BY COMPUTATIONAL INTELLIGENCE TECHNIQUES

Kavirayani Srikanth

Dept. of EEE, Gayatri Vidya Parishad College of Engineering(Autonomous), Visakhapatnam,Andhra Pradesh-530017, India Email: kavirayanisrikanth@gvpce.ac.in, ORCID ID: 0000-0002-5058-410X

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Abstract:

The pursuit of advanced composite materials with superior mechanical properties and performance characteristics has become increasingly critical in various engineering applications. This study presents a novel approach that leverages computational intelligence algorithms—specifically particle swarm optimization and flower pollination—to optimize the design and performance of composite materials used in dynamic systems, such as in the geometry and design of complex structures of airplane and bioreactor applications. By integrating computational intelligence with material science, we developed a framework to predict and enhance the properties of composite materials under various operational conditions. The proposed method involves a single objective and multi-objective optimization process that simultaneously considers factors such as weight reduction, tensile strength, and thermal stability. Through simulations and experimental validations, we demonstrate how the optimization of fiber orientation, matrix selection, and layering configurations can lead to significant improvements in the performance of composite materials. Additionally, we explore the application of sensor fusion techniques to monitor real-time performance metrics of these materials in dynamic environments, allowing for adaptive responses to varying operational conditions. The results indicate a marked improvement in the resilience and functionality of composite materials, paving the way for their enhanced application in aerospace engineering and bioprocessing. This work underscores the potential of computational intelligence in revolutionizing the design and application of composite materials, offering promising pathways for future research and industrial implementation.

Keywords: bioreactors, optimization, composite material, computational intelligence

1. Introduction

Bioreactors, essential tools in biotechnology and bioengineering, are vessels designed to cultivate microorganisms or cells under controlled conditions. Traditionally, bioreactors have been constructed from materials like stainless steel, glass, or concrete. However, in recent years, composite materials have emerged as promising alternatives due to their superior properties such as strength, lightweight, corrosion resistance, and designability. This literature survey aims to explore the recent advancements in the application of composite materials in bioreactor design and fabrication. This paper discusses an interesting interdisciplinary concept of a bioreactor on an aeroplane for future space missions. These can be used for Long-Duration Missions, In the future, with advanced technology, bioreactors could potentially be used to produce food or medicine on long-duration space missions. Also, for instance in

Airplanes could be used as platforms for research on microgravity bioreactors to study cellular and tissue growth in space. In this work, flower pollination algorithm and particle swarm optimization are used for evaluating this kind of a system.

Flower pollination is a nature inspired algorithm which has emphasis on a single objective unconstrained optimization [1-3]. The story of evolution of various flowering plants is an example by itself on indicating the efficiency of evolutionary process. Yang [4] has clearly developed and outlined the advantages based on how pollen gets transferred which becomes the approach for the development of the algorithm [5-8].

2. Methodology:

A generic energy function can be written by considering the system's total energy as a combination of kinetic, potential, thermal, and chemical energies. For any system, the energy function can be represented as:

$$E=T+V+U+Q \tag{1}$$

Where:

T: Kinetic energy (e.g., motion of fluids in a bioreactor or the airplane's velocity).

V: Potential energy (e.g., gravitational or elastic).

U: Internal energy (e.g., thermodynamic states, chemical reactions in a bioreactor, or heat in airplane systems).

Q: Energy exchange with the environment (e.g., heat transfer, work done).

By modeling these components, we can create a unified energy function tailored to the system's dynamics and constraints which could be as follows

$$\mathrm{E(x)} = \frac{1}{2}\mathrm{mv}^2 + \mathrm{mgh} + \alpha\mathrm{T}^2 - \beta \ln(\mathrm{P}+1) \tag{2}$$

or instance, a bioreactor or an airplane energy system with composite material effect can be represented as:

$$\mathrm{E(x)} = \frac{1}{2}\mathrm{mv}^2 + \mathrm{mgh} + \alpha\mathrm{T}^2 - \beta \ln(\mathrm{P}+1) + \gamma\frac{\sigma}{\mathrm{E_c}} + \delta_{\mathrm{K}} \tag{3}$$

where:

M: Mass (constant)

v: Velocity (decision variable)

g: Gravitational acceleration (constant, 9.81 m/s^2)

h: Height (decision variable)

T: Temperature (decision variable)

PPP: Pressure (decision variable)

α, β: System constants (e.g., heat capacity and compression factor)

$\frac{\sigma}{E_c}$: stress or elastic modules ratio, reflecting material deformation.

K: Thermal conductivity

γ , δ weighing factors for material related combinations.

This function combines kinetic energy, potential energy, thermal energy, and a logarithmic term representing environmental factors like pressure. These materials listed can be combined to form composite materials by pairing them with other materials to achieve desired properties. Here are some possibilities as shown in table 1. The parameters that are important are as follows:

a. Material Factor Coefficient:

This coefficient would depend heavily on the specific composite material used in the bioreactor and its structural components. It's a complex factor that would need to be determined through rigorous material testing and analysis. It might involve other factors like:

  b. Thermal conductivity:
  c. Strength-to-weight ratio: The material's ability to withstand stress while minimizing weight [9].
  d. Manufacturing costs: The cost of producing the material.
  e. Real-Time Space Applications:

In real-time space applications, these values might vary due to factors like:

- Microgravity: The effects of microgravity on material properties and heat transfer.
- Radiation exposure: The impact of radiation on material degradation and energy absorption.
- Temperature fluctuations: Extreme temperature changes in space.

Table 1. Specific Heat Capacities of various materials

Material	**Possible combinations for composite material formulation**	**Specific Heat Capacity**
Water	Can be used as a component in hydrogels or as a phase in certain emulsified composites.	4184 J/kg K
Aluminum	Commonly used in metal matrix composites (MMCs) by embedding ceramic particles (e.g., silicon carbide or alumina) to improve strength and wear resistance.	900 J/kg K
Titanium	Used as a matrix in high-performance composites, often reinforced with carbon fibers or ceramic particles for aerospace applications	523J/kg K
Stainless Steel	Can be reinforced with ceramic coatings or fibers to enhance properties like wear and corrosion resistance.	500 J/kg K

Flower pollination algorithm is a nature-inspired algorithm, based on the pollination of plants. Nature has its vivid variety of plants which have evolved over centuries by a natural pollination process. The method the species of flowers use for evolving is interesting and thought provoking. The movement pattern of pollen from one flowering plant to another is a significant way which could be used for applying it as an algorithm for engineering problems. Biotic, crosspollination may occur at long distance, and the pollinators such as bees, bats, birds and flies can fly a long distance, thus they can considered as the global pollination. In addition, bees and birds may behave as Levy flight behaviour, with jump or fly distance steps obeying a Levy distribution [4]. The algorithm for the pollination is given below where the fitness considered is a cumulative function of all the constraints that are acting on the system.

Algorithm A: Flower Pollination

```
1.  Initialize population
2.  Find the best solution for the designated fitness function (Energy Function)
```

$$E(x) = \frac{1}{2}mv^2 + mgh + \alpha T^2 - \beta \ln(P+1) + \gamma \frac{\sigma}{E_c} + \delta_K$$

(4)

```
3.  Provide switch probability
4.  While N<Generations
a.  For all flowers
i)  Evaluate levy distribution
ii) Evaluate global solution
5.  If new solution is better update previous solution
6.  Find current best solution
```

7. Designate the best positions as the pole locations.

Algorithm B: Particle Swarm Optimization:

Initialization: Initialize a population of particles (solutions).
Randomly assign initial positions and velocities to each particle.
Evaluation: Evaluate the fitness (energy) of each particle.

$$E(x) = \frac{1}{2}mv^2 + mgh + \alpha T^2 - \beta \ln(P + 1) + \gamma \frac{\sigma}{E_c} + \delta_K$$

Update personal best (pbest) and global best (gbest) positions.
Update Velocities: Update the velocity of each particle using the velocity update formula.
Update Positions: Update the position of each particle using the position update formula.
Termination: Check the termination criterion (e.g., maximum iterations, convergence).
If not met, go back to step 2.
Otherwise, return the gbest as the optimal solution.

3. Results:

The best solution indicate the FPA outperform particle swarm and could be used to optimize the system's motion by minimizing the total energy, which includes kinetic energy (energy of motion), potential energy (energy of position), and also the internal energy related to deformations or friction. The best solution array would then represent the optimal positions and velocities of the parts that minimize the overall energy consumption or maximize the system's efficiency.
The algorithm identified solutions that optimize energy use while considering composite material performance, leading to a more realistic and applicable result for systems employing advanced materials. It was found that the effect of material property in optimization is minimal.

Table 2. Scenarios for energy evaluation

Case id#	**Scenario 1**	**Best solution**	**Energy Value**
1	With Composite Material	[0. 0. 0. 1. 0. 0.60707465 0.]	-1.3862943611198906
2	Without Composite Material	[0. 0. 0. 1.]	-1.3862943611198906

Table 3. Best solutions for different materials

S. no	**Material**	**specific heat capacity of the material (J/kg K)**	**material factor coefficient:**	**Best Solution**
1	Water	4184	0.87	[-1.22564038e+103 1.00521161e+103 7.66427425e+102 1.23394278e+103 1.37598280e+103]
2	Aluminium	900	0.8~0.9	[-1.67141620e+103 6.42695552e+102 9.20947717e+101 1.65375725e+103 1.52469552e+103]
3	Titanium	523	3.0~4.5	
4	Stainless Steel	500	2.0~3.0	[-2.52387497e+103 7.34849481e+102 2.69330631e+102 1.64410221e+103 1.02123912e+103]
5	Carbon Fiber Reinforced Polymer	0.8~1.2	2.5~3.0	[-1.05662780e+103 -8.27219623e+102 3.51415630e+102 -1.53071363e+101 9.45598066e+101]
6	Magnesium alloys	~0.6–0.8	~1.02 kJ/kg·K.	[-1.05906370e+103 -6.22032626e+102 2.71265186e+102 4.87005095e+102 -1.17209271e+102]

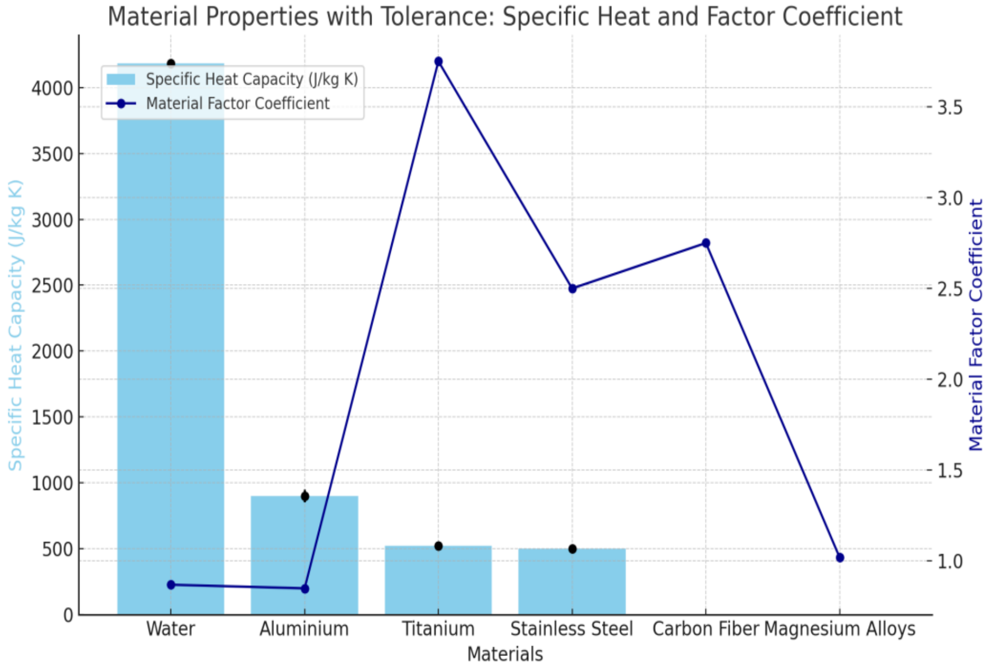

Fig. 1. Analytical view of the material properties with tolerance

4. Conclusions:

In some cases, the optimized energy is the same in both cases; it suggests that the additional material-specific terms in the energy function are not significantly affecting the optimization. This could happen due to several reasons: Scaling of Terms, Lack of Constraints, Flat Objective Landscape, and Weighting Factor Overlap.

While composite materials offer numerous advantages for bioreactor applications, several challenges remain to be addressed such as Cost of the Composite materials can be more expensive than traditional materials like stainless steel. Processing Complexity is another parameter as the fabrication of complex composite structures can be challenging and requires specialized expertise. Long-term Durability, i.e., the long-term performance of composite materials in bioreactor environments needs to be evaluated.

Future research should focus on developing innovative composite materials with improved biocompatibility, mechanical properties, and processability.

Additionally, exploring novel manufacturing techniques, such as 3D printing, can enable the fabrication of customized bioreactors with complex geometries. Composite materials have the potential to revolutionize bioreactor design and fabrication. By leveraging their unique properties, researchers and engineers can develop more efficient, versatile, and cost-effective bioreactors for a wide range of applications. Continued advancements in materials science and engineering will further expand the possibilities for the use of composite materials in this field.

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