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Smart Control of Vibrations in Functionally Graded Porous Wind Turbine Blades via Piezoelectric Materials

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Abstract: Piezoelectric materials possess the unique ability to convert mechanical stress into electrical voltage and vice versa, making them highly suitable for various smart engineering applications. One of their most promising uses is in the field of vibration energy harvesting, where ambient mechanical vibrations can be transformed into usable electrical energy. For instance, when integrated into roads, pavements, or structural components, piezoelectric sensors and actuators can harvest energy from dynamic loads such as moving vehicles or pedestrians. In renewable energy systems, particularly wind turbines, blade vibrations can lead to structural fatigue and efficiency loss. The integration of piezoelectric elements for active vibration control can significantly reduce unwanted oscillations and enhance operational stability and energy output. Simultaneously, functionally graded materials (FGMs) — advanced composites with spatially varying properties — are increasingly being used in the design of wind turbine blades and other mechanical components due to their ability to optimize strength and reduce stress concentrations. This research focuses on the active vibration control of tapered FGM beams with porous structures using embedded piezoelectric actuators. The modeling approach combines Euler-Bernoulli beam theory with the finite element method (FEM), and the governing equations are derived through Hamilton's principle to accurately capture the dynamic behavior of the system.

Keywords: Vibration control, Functionally Graded materials, Turbine blade, Piezoelectric materials, Finite element method

Introduction

The intrinsic multifunctional character of piezoelectric materials, which enables a bidirectional conversion between mechanical energy and electrical signals, has cemented their status as cornerstone elements in smart material systems (Mason, 1981). This phenomenon, manifesting as the direct piezoelectric effect (charge generation under stress) and its converse (strain induction under an electric field), is rooted in the non-centrosymmetric crystalline structure of these substances (Henderson, 2006). Pioneering compounds such as Lead Zirconate Titanate (PZT) ceramics are lauded for their exceptional electromechanical coefficients and thermal stability, rendering them ideal for demanding roles in actuators and high-sensitivity sensors. In parallel, polymers like Polyvinylidene Fluoride (PVDF) offer complementary advantages of mechanical flexibility and low acoustic impedance, facilitating their integration into wearable devices and conformal transducers.

A domain where this energy-harvesting capability is being aggressively leveraged is ambient vibration scavenging. The strategic embedding of piezoelectric generators within transportation infrastructure—from roadways in Toulouse, France, to railway lines in Japan—exemplifies a pragmatic approach to sustainable energy. These installations capture otherwise dissipated kinetic energy from passing vehicles and trains, converting it into electricity to power ancillary systems such as signage and monitoring networks. Beyond mere power generation, the continuous data stream from these embedded sensors provides an invaluable tool for structural health monitoring (SHM), allowing for the real-time detection of degradation and the facilitation of predictive maintenance, thereby enhancing public safety and asset management (Safaei et al.,2019).

Notwithstanding these advancements, the pursuit of enhanced performance and durability in engineering structures has catalyzed the development of Functionally Graded Materials (FGMs). Unlike conventional laminated composites that suffer from discrete interfacial stress concentrations, FGMs are architected with spatially continuous gradients in composition and microstructure (Mason, 1981; Henderson, 2006; Safaei et al., 2019). This tailored microstructure, for instance a smooth transition from a thermally resistant ceramic surface to a ductile metallic core, optimally reconciles conflicting property requirements. In the context of wind turbine blades, this gradient architecture can be designed to enhance aerodynamic efficiency, mitigate fatigue-induced damage, and reduce overall structural mass—a critical factor for the economic viability of large-scale offshore installations.

However, the fabrication of FGMs, often via powder metallurgy or additive manufacturing techniques, frequently introduces microscopic porosities as an inherent byproduct. While a controlled porosity gradient is sometimes deliberately engineered for specific applications, such as biocompatible implants that mimic bone structure, its unintended presence typically acts as a defect. These pores can significantly alter the local stress field, reduce the effective elastic modulus, and consequently diminish the overall structural stiffness and fatigue life. This interplay between material gradation and porosity presents a complex challenge that directly influences the dynamic vibrational response of FGM components.

The incorporation of Functionally Graded Materials (FGMs) into wind turbine blade manufacturing constitutes a notable advancement within the renewable energy sector (Mahapatra et al.,2021). Characterized by a continuous gradient in their chemical composition or microstructure, FGMs facilitate the optimization of the blades' mechanical and thermal properties, thereby augmenting their overall strength and durability. This tailored material design enables the blades to more effectively endure the variable stress states and vibrational loads induced by wind gusts, consequently mitigating the risk of crack propagation and structural failure. Furthermore, FGMs can be engineered to improve the aerodynamic efficiency of the blades, leading to enhanced performance of the wind turbines (Hu et al.,2013). This technology also permits a reduction in blade mass without a corresponding sacrifice in structural integrity, a critical consideration for large-scale offshore applications (https://innovation.engie.com). In summary, the integration of FGMs presents considerable potential for increasing the reliability and efficiency of wind energy systems, thereby contributing to more sustainable and environmentally benign power generation. It is important to note, however, that the fabrication processes for these innovative materials can introduce porosities, which are known to significantly impair their mechanical performance.

Beams represent fundamental structural components extensively utilized in aerospace engineering and various other industries. Among these, variable-section beams are particularly significant in the construction and structural engineering sectors due to their considerable advantages, such as superior stiffness and structural stability. Their implementation enables a reduction in material usage and labor costs while providing enhanced rigidity. The dynamic behavior of non-uniform section beams has been investigated by El Harti et al. based on Timoshenko's theory (El Harti et al., 2022). Furthermore, Shabani and Cunedioglu (2020) conducted a free vibration analysis of cracked, functionally graded non-uniform beams. El Harti et al. have also examined the influence of porosity in FGM materials (9,10) as well as the effects of thermal loading (El Harti et al., 2020; El Harti, 2021; El Harti et al., 2022).

Building upon this foundation, the present work aims to address a specific gap: the active vibration control of a tapered, power-graded (P-FGM) porous beam using a distributed network of piezoelectric sensor/actuator pairs. The mathematical model is developed within the framework of the Euler-Bernoulli beam theory and discretized via the Finite Element Method (FEM). The primary objective is to employ an advanced control methodology to rigorously investigate the suppression of transient vibrations, with a particular focus on quantifying the individual and coupled effects of taper geometry, material power-law index, and porosity fraction on the system's controlled and uncontrolled dynamic performance.

Mathematical Modeling

The modeling of the Functionally Graded (FG) material behavior is based on a power-law distribution to describe the continuous variation of mechanical properties through the beam's thickness, from a pure metal surface at $z = -h/2$ to a pure ceramic surface at $z = +h/2$. The volume fraction of the ceramic phase is defined by:

$$V_c = \left(\frac{2z + h}{2h}\right)^k = 1 - V_m \tag{1}$$

where V_c and V_m represent the volume fractions of the ceramic and metallic constituents, respectively, and k is the power-law exponent governing the material gradation profile. To account for manufacturing imperfections, such as micro-porosity introduced during sintering, the effective Young's modulus $E(z)$ and mass density $\rho(z)$ are expressed as:

$$E(z) = E_m + (E_c - E_m)\left(\frac{2z + h}{2h}\right)^k - \frac{n}{2}(E_c + E_m) \tag{2}$$

$$\rho(z) = \rho_m + (\rho_c - \rho_m)\left(\frac{2z + h}{2h}\right)^k - \frac{n}{2}(\rho_c + \rho_m) \tag{3}$$

The porosity parameter n with ($n = 0, 0.1, 0.2$) quantifies the imperfection level, where $n = 0$ corresponds to a perfect, non-porous FGM. The beam's cross-sectional area $A(x)$, width $b(x)$, and moment of inertia $I_y(x)$ are described by the following geometric relations (El Harti et al., 2024):

$$b(x) = b_0\left(1 - C_b\frac{x}{L}\right)^m \tag{4}$$

$$A(x) = A_0\left(1 - C_b\frac{x}{L}\right)^m \tag{5}$$

$$I_y(x) = I_{y_0}\left(1 - C_b\frac{x}{L}\right)^m \tag{6}$$

To ensure positive values for $A(x)$ and $I_y(x)$, the width taper ratio C_b must satisfy $0 \le C_b < 1$. This ratio is calculated from the widths at the fixed (b_0) and free (b) ends:

$$C_b = 1 - \frac{b}{b_0} \tag{7}$$

The initial cross-sectional area and moment of inertia at the clamped end $(x = 0)$ are:

$$A_0 = b_0 h \tag{8}$$

$$I_{y_0} = \frac{b_0 h^3}{12} \tag{9}$$

Adopting the Euler-Bernoulli beam theory, the displacement field at any point is defined by:

$$u(x, y, z, t) = z\frac{\partial w(x, t)}{\partial x} \qquad w(x, y, z, t) = w(x, t) \tag{10}$$

The resulting non-zero strain and stress components are:

$$\varepsilon_{xx} = z\frac{\partial^2 w(x, t)}{\partial x^2} \qquad \sigma_{xx} = Ez\frac{\partial^2 w(x, t)}{\partial x^2} \tag{11}$$

The governing equations are derived using Hamilton's principle:

$$\delta \int_{t_1}^{t_2} (U - T - W)dt = 0 \tag{12}$$

where U is the strain energy, T is the kinetic energy, and W is the work done by external forces. The strain energy U and kinetic energy T are formulated as:

$$U = \frac{1}{2}\iiint_V \{\sigma\}^T\{\varepsilon\}\, dV = \frac{1}{2}\int_0^l \iint_A Ez^2 \left(\frac{\partial^2 w}{\partial x^2}\right)^2 dA\, dx \tag{13}$$

$$T = \frac{1}{2}\iiint_V \rho \left(\frac{\partial w}{\partial t}\right)^2 dV = \frac{1}{2}\int_0^l \iint_A \rho \left(\frac{\partial w}{\partial t}\right)^2 dA\, dx \tag{14}$$

The work W done by a distributed transverse load $f(x,t)$ is:

$$W = \int_0^l fw\, dx \tag{15}$$

The Euler-Bernoulli beam finite element is employed, which assumes that plane sections normal to the neutral axis remain plane and normal after deformation. This implies that the slope θ is the first derivative of the transverse deflection w. For this element type, the deflection is approximated by a cubic polynomial in xx, as it must accommodate four nodal degrees of freedom (two deflections and two slopes). The deflection $w(x,t)$ within an element is interpolated as:

$$w(x,t) = \boldsymbol{N^T}(x)\boldsymbol{qe}(t) \tag{16}$$

where $\boldsymbol{N}(x)$ is the vector of Hermite shape functions $[N1, N2, N3, N4]$, and $\boldsymbol{qe} = [w_1 \quad \theta_1 \quad w_2 \quad \theta_2]^T$ is the vector of nodal displacements and rotation. The curvature $w''(x,t)$ and velocity $w'(x,t)$ are given by:

$$[w'(x,t)] = [n_2^T][q] \tag{17}$$

$$[w''(x,t)] = [n_1^T][q] \tag{18}$$

$$[\dot{w}(x,t)] = [n_3^T][\dot{q}] \tag{19}$$

Applying the Lagrange equations leads to the elemental equation of motion:

$$M\ddot{q} + Kq = f(t) \tag{20}$$

The elemental mass and stiffness matrices for the FGM core and the piezoelectric layers are derived as follows:

$$[M] = [M^{FGM}] + [M^s] + [M^a] \tag{21}$$

$$[K] = [K^{FGM}] + [K^s] + [K^a] \tag{22}$$

The control force produced by the actuator is obtained by:

$$f_{ctr} = E_p d_{31} b \bar{z} \int_{l_p} n_2 dx \, V^a(t) \tag{23}$$

and as long as there are two piezoelectric actuators symmetrically bonded to the structure to eliminate the membrane effect, there are two control forces, represented as follows:

$$f_{ctr1} = -f_{ctr2} = h \, V^a(t) = h \, u(t) \tag{24}$$

With

$$h^T = E_a d_{31} b \bar{z} [-1 \quad 0 \quad 1 \quad 0] \tag{25}$$

Using Rayleigh's proportional damping:

$$C = \alpha M + \beta K \tag{26}$$

Dynamic equation of the structure and the equation of control are given by:

$$M^* \ddot{g} + C^* \dot{g} + K^* g = f^*_{ext} + f^*_{ctr1} + f^*_{ctr2} \tag{27}$$

The state space model in MIMO (Multi In Multi Out) mode is given by:

$$\dot{x} = Ax(t) + Bu(t) + Er(t) \tag{28}$$

$$y(t) = C^T x(t) + Du(t) \tag{29}$$

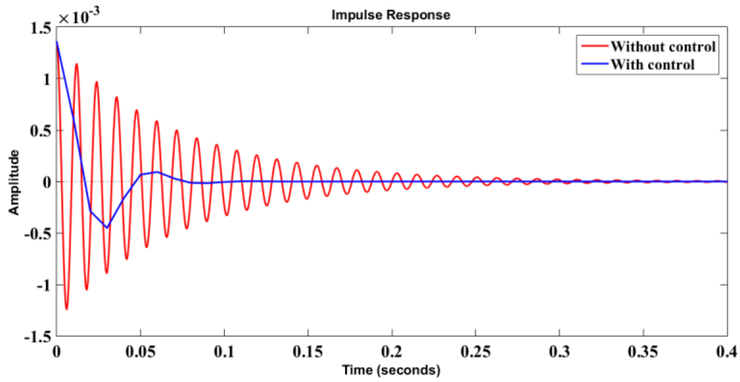
The method of LQG (Linear Quadratic Gaussian) is a method widely used by the mechanics (Sanbi, 2010), Boyere, E. (2011)), based on the desire to minimize performance J index of the form:

$$J(u) = \int_0^\infty (x^t Q x + u^t R u) \, dt \tag{30}$$

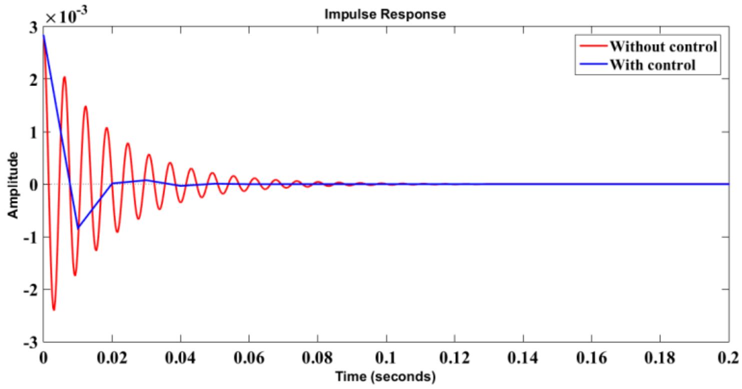
Results and Discussion

This research examines the active vibration control of a cantilevered, functionally graded material (FGM) beam characterized by a variable cross-section. The study focuses on tree key parameters: the porosity distribution within the FGM, the power index and the beam's taper ratio. The power law is employed to describe the continuous variation of material properties through the thickness. The numerical model comprises a beam of dimensions 0.5 m in length, 0.02 m in width, and 0.0001 m in height. A symmetric arrangement of four piezoelectric layers, bonded to the top and bottom surfaces, is integrated into the design to perform simultaneous sensing and actuation. Figure 1 shows the variation of the porosity index n, with the power index k and width b held constant.

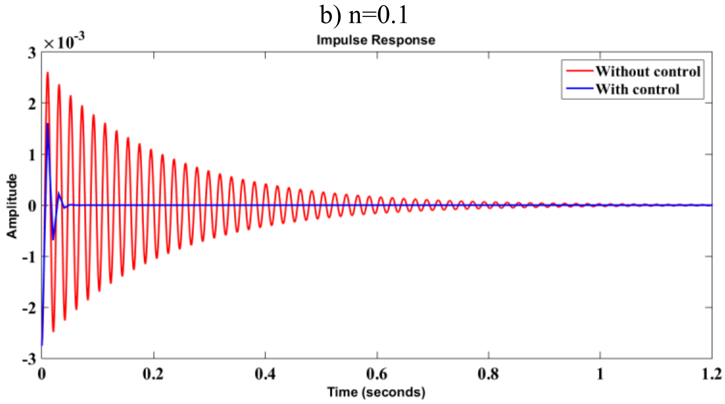
Figure 1 indicates that the vibration amplitude increases with the porosity index. The remark that an increase in the porosity index leads to higher vibration amplitudes is strongly supported by the data presented in Figure 1. The graph clearly shows a positive correlation between the two parameters. Specifically, as the porosity index increases from [n=0] to [n=0.2], the vibration amplitude rises from [1.5] to [3]. This trend is consistent across the observed range, indicating that the material's propensity to vibrate is directly influenced by its void content.



a) $n = 0$



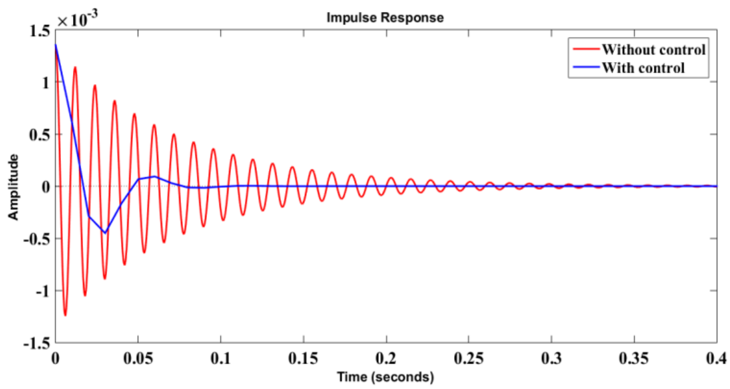
b) n=0.1



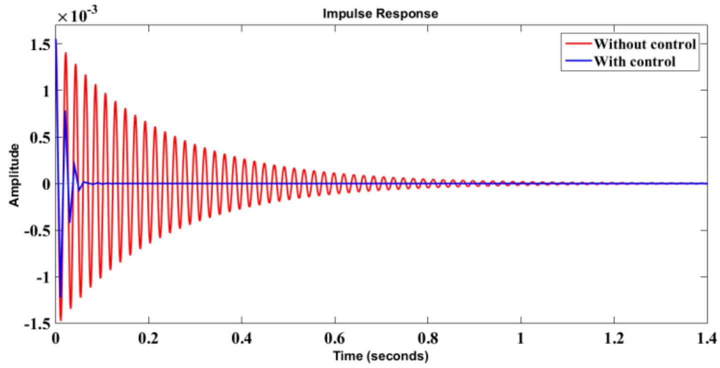
c) n=0.2

Figure 1. Variation of the Porosity İndex n ($b = 2.2$; $k = 0.2$)

Figure 2 depicts the relationship of the power index k for constant porosity index n and width b. Figure 2 demonstrates that the system's vibrational energy is directly driven by the power index. This is a logical outcome, as a higher power index supplies more energy, forcing the system to oscillate with greater amplitude.



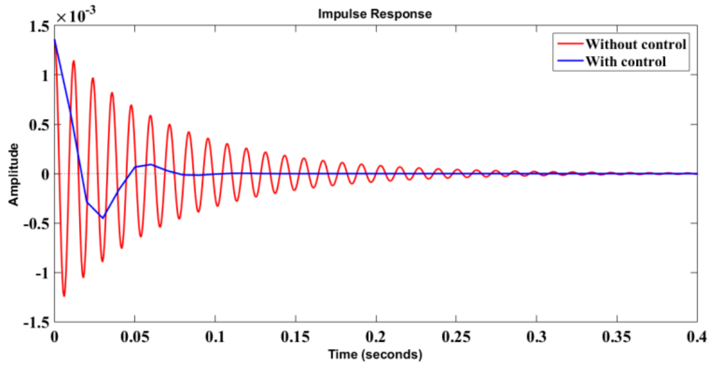
$k = 0.2$



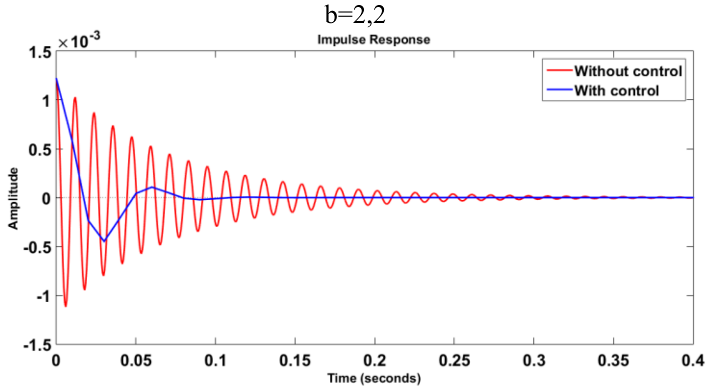
$k = 50$

Figure 2. Variation of power index k ($b = 2.2$; $n = 0$)

Figure 3 presents the variation in the width b, while the porosity index n and power index k are kept fixed. Figure 3 reveals a distinct inverse relationship between the width and the resulting vibration amplitudes. This trend can be physically justified by considering that an increase in width enhances the structural stiffness and inertia of the system. A stiffer structure is inherently more resistant to deformation, leading to a lower vibrational response for the same level of excitation. Consequently, width emerges as a key geometric parameter for controlling and dampening vibrations in this context.



b=2,2



b=2,8

Figure 3. Variation of the width b, ($k = 0.2$; $n = 0$)

Conclusion

This study has presented a comprehensive numerical investigation into the active vibration control of a cantilevered, functionally graded (FGM) beam with a tapered geometry and integrated piezoelectric sensor/actuator pairs. The developed model, grounded in Euler-Bernoulli beam theory and discretized via the Finite Element Method (FEM), successfully captured the complex dynamic behavior of the system under the coupled influences of material gradation, geometric taper, and inherent porosity.

The primary objective was to rigorously analyze the suppression of transient vibrations using an LQG control strategy, with a specific focus on quantifying the individual and synergistic effects of key parameters. The results and discussion yielded several critical insights:

- Porosity Impact: A strong positive correlation was established between the porosity index and vibration amplitudes. An increase in porosity, which effectively reduces the material's stiffness, was shown to significantly amplify the vibrational response, underscoring the detrimental effect of manufacturing imperfections on dynamic performance.
- Power-Law Index Influence: The power-law index, governing the material gradation profile, was confirmed as a direct driver of vibrational energy. Higher values of this index resulted in increased oscillation amplitudes, highlighting the critical role of the FGM composition in the system's dynamic characteristics.
- Geometric Stiffening via Width: In contrast, the beam's width was identified as a key geometric parameter for vibration mitigation. The analysis revealed a distinct inverse relationship, where an increase in width enhanced the structural stiffness and inertia, leading to a substantial reduction in vibration amplitudes.

In summary, this work elucidates the competing effects of material and geometric properties on the vibrational behavior of smart FGM structures. It demonstrates that while certain factors like porosity and material gradation can exacerbate vibrations, their negative impact can be effectively counteracted through strategic geometric design (e.g., increasing width) and the application of advanced active control systems using piezoelectric materials. The findings provide valuable guidelines for the optimal design and control of next-generation wind turbine blades and similar lightweight structures, where managing vibrations is paramount for structural integrity, longevity, and operational efficiency. Future work could explore the effects of different porosity distributions, more complex geometries, and nonlinear control strategies.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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