Design of Microneedles Inspired by the Structural Mechanics of the Mosquito's Piercing Fascicle

S. R. Mahmoud[1], Habeeb M. Al-Solami[2], S. I. Ali [3], Afaf S. Alwabli[4], Ghadeer Bukhari[4], Jabr Aljedani[1], Khalil S. Al-Basyouni[5], Mohammed A. Balubaid[6]

[1]GRC Department, Applied College, King Abdulaziz University, Jeddah, Saudi Arabia.

[2]Department of Biological Sciences, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia.

[3]Department of Mathematics, Faculty of Science, Al-Azhar University, Nasr City, Cairo, Egypt.

[4]Department of Biological Sciences,College of Science & Arts, Rabigh Campus, King Abdulaziz University, Jeddah, Saudi Arabia.

[5]Department of Mathematics, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia.

[6]Department of Industrial Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

srhassan@kau.edu.sa

Abstract.

This study investigates the structural mechanics of the mosquito's piercing fascicle to provide a biomimetic framework for designing microneedles with enhanced functionality. A mechanical approach is applied to accurately determine the critical buckling loads of the fascicle, accounting for axial non-homogeneity. Using the power series method, the governing differential equation with varying coefficients is solved under clamped and free-end boundary conditions. The derived characteristic equation offers precise predictions of critical buckling loads, validated through comparisons with experimental data for both homogeneous and non-homogeneous structures. Additionally, the study analyzes the influence of labium support and axial gradient parameters, emphasizing the vital role of lateral support in ensuring structural stability. The findings contribute to the development of advanced microneedles for minimally invasive procedures and efficient drug delivery systems, addressing challenges relevant to veterinary and medical applications.

Keywords: Critical buckling; Structural mechanics; Biomimetics; Microneedles; Mosquito fascicle; Stability analysis; Axial gradient; Veterinary innovations.

1. Introduction

The integration of biomimetic principles in the design of medical devices has opened new frontiers in improving their functionality and efficiency. This research, which explores the structural mechanics of the mosquito's piercing fascicle, offers a groundbreaking approach to the development of microneedles. The relevance of this study aligns seamlessly with the multidisciplinary focus of *Cattle Practice*, as it emphasizes the importance of innovation in structural mechanics and biomedical engineering. By leveraging the unique stability and efficiency of mosquito-inspired structures, this research aims to address challenges in minimally invasive medical procedures and drug delivery systems. Such advancements are particularly relevant in veterinary medicine and animal healthcare, highlighting the potential for interdisciplinary solutions that benefit both humans and animals.

Advances in microneedle technology and the reduction of insertion force are relevant to microfabrication and nanotechnology. These technologies can be applied to the development of miniature devices and systems for a wide range of applications, including electronics, sensors, and drug delivery systems. The study of mechanical forces in mosquito fascicles and their interaction with elastic foundations can provide valuable insights into material behavior, especially in the context of biological

materials. This knowledge can lead to the development of materials with enhanced properties for various applications. Puncturing the human skin with a hollow needle is perhaps the most common invasive medical procedure to inject fluids into or extract fluids from the human body. Regardless of the size of the needle, unless an anesthetic is used, it is at least uncomfortable, if not painful. A series of recent studies have discussed strategies taken by nature to prevent buckling and, in effect, improve the performance of percutaneous instruments (e.g., microneedles). Mosquito fascicles with elastic foundations have many applications in modern bioengineering and pose significant technical problems in many structural designs. The Winkler elastic foundation model is pivotal for assessing stability in various engineering applications. Alkenani *et al.* [1] and Mahmoud *et al.* [2] explored the mechanical forces in mosquito fascicles, contributing to advancements in medical device innovation.Bhoyar *et al.* [3], Bondla *et al.* [4], and Mellal *et al.* [5] examined structural responses on elastic foundations, while Bourada *et al.* [6] analyzed the dynamic stability of reinforced beams. Jaiswal and Muthuswamy [7] provided insights into the instability of mosquito fascicles, inspiring microneedle design. further enhance the mosquito's ability to efficiently penetrate the skin.These anatomical adaptations, as highlighted by Jaiswal and Muthuswamy [7], demonstrate the mosquito's remarkable biomechanical efficiency and provide inspiration for bioengineered designs. Zimmermann *et al.*

[8] advanced microneedle technology for glucose monitoring. Gattiker *et al.* [9] introduced the 'e-mosquito' for blood sampling. Yang and Zahn [10] and Qi *et al.* [11] focused on reducing insertion force and adding antibacterial properties to microneedles.

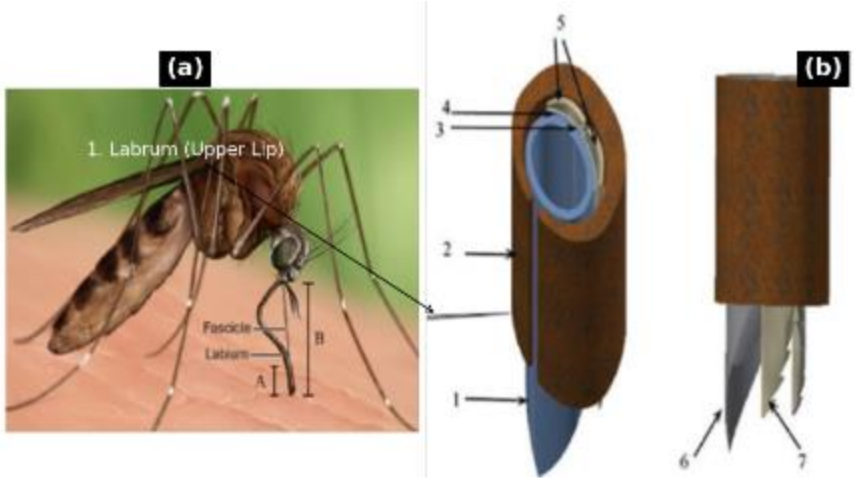

Fig. 1 (a) The mosquito female Aedes aegypti; (b) the parts of the mosquito proboscis.

Figure 1 illustrates the female mosquito *Aedes aegypti* and the structural components of its proboscis. The labrum, labeled as (1), functions as the upper lip-like structure, while the labium (2) serves as a protective sheath surrounding the fascicle. The hypopharynx (3) is a specialized tube that delivers saliva during the biting process. Additionally, the mandibles (4) act as cutting edges to pierce the skin, and the maxillae (5) feature a saw-like design that facilitates penetration. The quill-shaped tip of the labrum (6) and the saw-shaped tip of the maxilla (7)

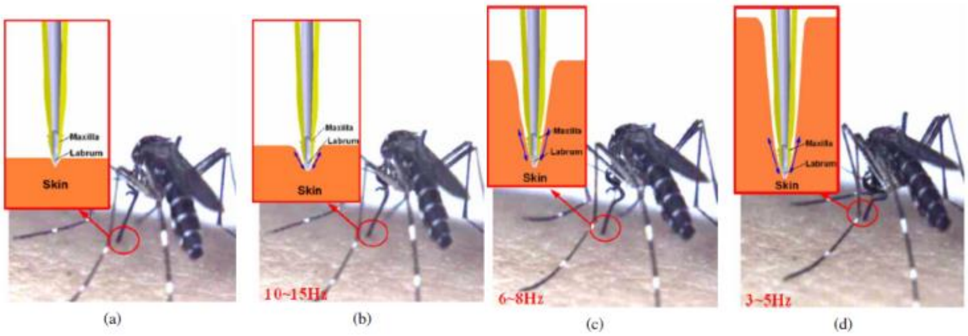

Fig. 2. *The process of mosquito fascicle insertion was detected using an HSV camera.*

The results of our model confirm the critical role of lateral support in maintaining structural stability, aligning with well-established experimental findings by Jaiswal and Muthuswamy [7] and Kong and Wu [22]. Figure 2 illustrates the process of mosquito fascicle insertion captured using an HSV camera, as detailed by Kong and Wu [22]. (a) The tip of the mosquito's fascicle penetrates the skin. (b) The mosquito uses its micro-sawtoothed maxillae to saw its way into the human skin at a frequency of approximately 10–15 Hz. (c) The mosquito continues to use the fine-toothed maxillae to saw its way with a frequency of nearly 6–8 Hz. (d) Finally, the oscillation frequency decreases to 3–5 Hz as the mosquito completes penetration and begins to suck blood. Pailler-Mattei *et al.* [12] linked the mechanical properties of skin to penetration depth, enhancing the understanding of the skin's response to microneedle insertion. Yang and Zahn [13], Newton *et al.* [14], Davis *et al.* [15], and Vincent *et al.* [16] contributed to the knowledge of microneedle insertion dynamics and insect cuticle mechanics. Using electrical conductivity measurements and a load cell for accurate penetration force measurement, the penetration force was reported as 10 mN, compared to a minimum force of 100 mN, as stated by Vincent and Wegst [16]. Continuing the pursuit of advanced materials and structural integrity, Alwabli *et al.* [17] meticulously investigated the nanoscale buckling properties of isolated protein microtubules, offering a novel perspective on materials at the molecular level. The findings complement the structural analysis of carbon nanotube-reinforced concrete beams, where Bousahla *et al.* [18] examined their buckling and dynamic behavior, emphasizing the role of the integral-first shear deformation theory in understanding these advanced materials. The dynamic and bending properties of protein microtubules have also been explored by Benmansour *et al.* [19], with the modified strain gradient theory revealing new insights into the mechanical behavior of such nanostructures. Research by Ghandourah [20] on the nonlocal elasticity theory for protein microtubules has furthered our understanding of their mechanical behavior, contributing to the development of smarter materials and structures. Bioinspired strategies for buckling prevention, as reviewed by Sakes *et al.* [21], shed light on nature's solutions to engineering challenges, providing a unique perspective for the development of innovative instruments. This is echoed in the mathematical modeling efforts by Barham [22] for the mechanics of mosquito bites, which hold significant relevance for microneedle design, thereby influencing biomedical engineering approaches The elegant bio-micro-electro-mechanical system of the mosquito proboscis, as studied by Barham [22], and the mechanics of mosquito bites with implications for microneedle design, as examined by Kong and Wu [23], showcase the intersection of biology and engineering. These studies offer a blueprint for developing medical devices that mimic the efficiency and finesse of natural systems. In the realm of structural mechanics, the influence of elastic end supports on the dynamic stability of Beck's column has been investigated by Ramasubramanian et al. [24] and

Caddemi *et al.* [25], addressing the challenge of stability in structures with weak sections. Methods to enhance linear stability, providing innovative solutions to classical problems in structural engineering, have been proposed by Ferretti and Luongo [26]. The concept of smart structures has been advanced by Rao and Singh [27], where strategies for enhancing the buckling load capacity of columns are suggested. Such advancements are pivotal for the design of modern infrastructures that require adaptive and resilient materials. A novel power series method to solve second-order partial differential equations, presented by Kurulay and Bayram [28], showcases the importance of advanced mathematical tools in tackling complex engineering problems. The interplay between material properties and structural behavior is highlighted by Zerrouki *et al.* [29], who explored the effects of nonlinear distribution of functionally graded materials on the mechanical properties of composite beams. This is further complemented by the exact solutions for buckling of structural members provided by Wang, Wang, and Reddy [30], offering precise analytical approaches for engineers and researchers.

The buckling of functionally graded and elastically restrained non-uniform columns is rigorously addressed by Singh and Li [31], where the stability of structures under various loading conditions is explored. The mechanical behavior and physical properties of protein microtubules within living cells using nonlocal beam theory, bridging the gap between material science and biological systems, have been delved into by Alhebshi *et al.* [32]. A mathematical approach to studying the effects of rotation, magnetic fields, and initial stress in non-homogeneous anelastic hollow cylinders is presented by Al-Basyouni and Mahmoud [33], providing insights into the behavior of materials under complex environmental conditions. The dynamical behavior of orthotropic elastic materials using analytical solutions is tackled by Balubaid *et al.* [34], and Mahmoud et al. [35-37] offering a deeper understanding of material responses to dynamic loading. Finally, the innovative work by Shoffstall *et al.* [38] draws inspiration from the mosquito to develop a strategy for implanting microprobes into the brain. This bioinspired approach could revolutionize medical procedures, showcasing the potential of interdisciplinary research that spans the domains of biology, material science, and mechanical engineering. These collective research efforts not only shed light on the current state of knowledge in material and structural engineering but also pave the way for future innovations that draw inspiration from the natural world. The convergence of theoretical models, empirical studies, and bioinspired designs represents the frontier of modern engineering research, driving forward the development of materials and structures that are both advanced and aligned with natural principles.

In the present paper, a power series method is introduced to analyze the buckling behavior of how the mosquitos use their fascicle and start to penetrate the human skin without any pain, and a biomathematical model for the behavior of the mosquito fascicle under the labium support and axial load has been demonstrated. Regarding the theoretical results, most of the microneedle designs, which can be polymeric, small in size, and have the ability to penetrate the human skin, can be improved and developed.

2. Formulation for problem

The non-homogeneous mosquito fascicle with a continuous elastic foundation under the influence of the applied axial load is investigated. The properties of the materials and cross-section are supposed to vary along the axial direction. For non-homogeneous mosquito fascicle, the governing differential equations on the elastic foundation may be written as:

$$\frac{d^2}{dx^2}\left[D(x)\frac{d^2w(x)}{dx^2}\right] + P\frac{d^2w(x)}{dx^2} + (\mathrm{k} - \mathrm{m}\omega^2)w(x) = 0, \quad 0 < x < \mathrm{L}, \qquad (1)$$

, k is the uniformly distributed laterally of stiffness per unit length; $D(x) = E(x)I(x)$ is the flexural rigidity which depends upon the axially graded Young modulus of elasticity $E(x)$, and spatially varying geometry with the moment of cross-section inertia $I(x)$; P is the axial compressive load at the centroidal axis, where $P > 0$ corresponds to compressive loading and $P < 0$ to tensile loading, respectively, and simplicity it, by introducing the non-dimensional coordinate $\xi = x/L,\ 0 < x <$ L, we can write the governing equation as:

$$\frac{d^2}{d\xi^2}\left[D(\xi)\frac{d^2w(\xi)}{d\xi^2}\right] + \lambda^*\frac{d^2w(\xi)}{d\xi^2} + (\alpha^* - \mathrm{m}\omega^2)w(\xi) = 0, \quad 0 < \xi < 1, \qquad (2)$$

Where x, L, w and are the axial coordinate, the length of the mosquito fascicle, and the transverse displacement, respectively; $\lambda^* = PL^2$ is the normalized critical load, $\alpha^* = kL^4$ is the parameter of normalized restraint stiffness, where one denotes $D(x)$and $w(x)$as $D(\xi)$and $w(\xi)$, respectively, ω is natural frequency; m is mass per unit length; $m = \rho A$, ρ is the material density of member; A: cross-sectional area. For the present problem, it is sufficient to determine the characteristic values λ^* of the resulting governing equation (2), which is related to the critical buckling loads of mosquito fascicle via $\lambda^* = PL^2$. Since critical buckling loads are closely related to the end supports of the mosquito fascicle, it is instructive to give expressions for relevant, familiar end conditions such as clamped and free ends, which can be given in terms of w as follows:

$$Clamped\ end\ (C): \qquad w = 0, \qquad and \qquad \frac{dw}{d\xi} = 0, \tag{3a}$$

$$Free\ end(F): \qquad \frac{d^2w}{d\xi^2} = 0, \quad and \quad \frac{d}{d\xi}\left[D(\xi)\frac{d^2w}{d\xi^2}\right] + \lambda^* \frac{dw}{d\xi} = 0, \tag{3b}$$

Mathematically, it is often difficult to find exact closed-form solutions for non-uniform mosquito fascicles. So, it is much desired to find a method as power series method to exactly determine the critical buckling loads of such mosquito fascicles.

3. The solution of the model

To solve our model, we take an axially graded and non-uniform mosquito fascicle as a cantilever (C–F) with the clamped end at $\xi = 0$ and a free end at $\xi = 1$. First of all, we expand $w(\xi)$ as a power series. Or rather, if neglecting sufficiently small error, the unknown $w(\xi)$ can be approximately expanded as

$$w(\xi) = \sum_{i=0}^{N} ci\frac{\xi^i}{i!}, \qquad 0 \le \xi \le 1, \tag{4}$$

Where c_i are unknown coefficients, and N is a certain positive integer. Applying the clamped boundary conditions at $\xi = 0$, substituting (4) into the boundary conditions, one gets

$$C_0 = 0, \qquad C_1 = 0.$$

Similarly, if considering the free end as a boundary condition at $\xi = 1$, we can obtain

$$\sum_{i=0}^{N} \frac{i(i-1)}{i!} c_i = 0, \tag{5}$$

$$\sum_{i=0}^{N} \frac{i}{i!}[D(1)(i-2) + D'(1)(i-1) + \lambda^*]\ c_i = 0, \tag{6}$$

Where the prime stands for the derivative of a function with respect to the argument. To solve the linear equations (5-6), another N − 3 independent equations are needed; inserting (4) into the equation (2) for each case leads to

$$\sum_{i=0}^{N}[C_i^4 D(\xi)\ +2C_i^3 D'(\xi)\xi\ +C_i^2 D''(\xi)\xi^2+\alpha^*\xi^4]\,\frac{\xi^{i-4}}{i!}c_i+\lambda^*\sum_{i=0}^{N}C_i^2\frac{\xi^{i-2}}{i!}c_i=0, \quad (7)$$

and

$$C_i^4\ = i(i-1)(i-2)(i-3), \qquad C_i^3\ = i(i-1)(i-2), C_i^2 = i(i-1).$$

We multiply both sides of (7) by ξ j (j = 0, 1, 2, . . . , N − 4) and then integrate with respect to ξ between 0 and 1, yielding N − 3 linear algebraic equations of unknown coefficients c_i:

$$\sum_{i=0}^{N}\left(T_{1ji}+\lambda^* T_{2ji}\right)c_i\ =0, \qquad j=0,1,2,\ldots,N-4, \quad (8)$$

$$T_{1ji}=\int_0^1[C_i^4 D(\xi)+2C_i^3 D'(\xi)\xi+C_i^2 D''(\xi)\xi^2+\alpha^*\xi^4]\,\frac{\xi^{j+i-4}}{i!}d\xi \quad (9)$$

$$T_{2ji}=\int_0^1 C_i^2\frac{\xi^{j+i-2}}{i!}d\xi.$$

Ultimately, making use of Eqs. (5-6) and (8), we can obtain a system of linear algebraic equations for unknown coefficient C_i. To obtain a nontrivial solution, then

$$\mathrm{Det}(T)=0, \quad (10)$$

Where T is the square coefficient matrix of order (N + 1) × (N + 1) for the linear equations, consequently, normalized critical load λ^* is obtained from the characteristic equation.

4. Discussion and results

In order to use a power series method to investigate the effect of axial non-homogeneity in mosquito fascicle on the critical buckling loads, we consider the polynomials flexural rigidities of the form , when , this is linearly varying of the axial rigidity, and when for parabolically varying axial rigidity. for non-uniform mosquito fascicles with elastic restraint for the dimensionless critical buckling loads for clamped free boundary conditions are evaluated in Fig 3 with 2, respectively. Moreover, we have calculated the critical buckling loads by the parameter for clamped and free ends mosquito fascicle with different normalized elastic restraints When N in eq.(4) takes different values more than 11.The calculated results affirm the accuracy of the critical buckling loads for clamped and free ends, aligning with prior findings by Singh and Li [30], Zerrouki *et al.* [28], Wang *et al.* [30]. It is also detected that the monotonical increase of the critical buckling loads with the increase of the normalized parameter of the restraint stiffness α shows the elastic foundation plays a significant role in measuring the critical buckling loads of the mosquito fascicle.

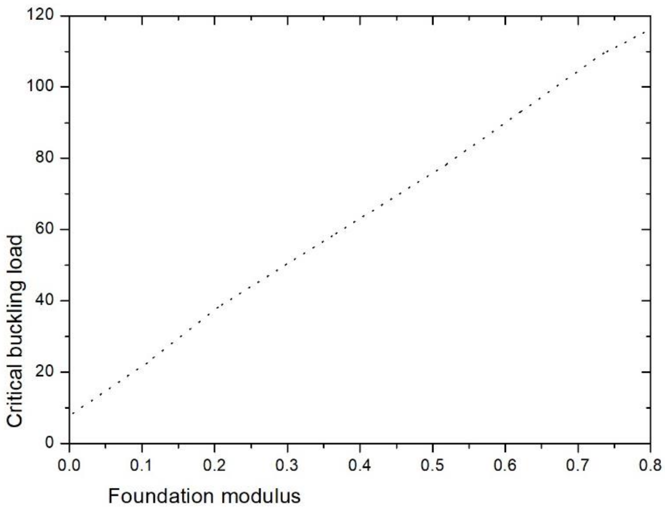

Fig. 3 Effect of foundation modulus on the critical buckling load.

From Fig. 3, It is also detected that the obtained calculated results reach an agreement very well with the existing previous results. Particularly, our calculated results closely match the results acquired when N is more than 11. Fig. 3. Shows the effects of elastic foundations α on the dimensionless critical buckling loads λ for non-uniform mosquito fascicle of parabolically varying axial rigidity D(ξ) = c0(1 + ξ)2. Furthermore, the influence of elastic foundations on the critical buckling loads for the clamped and free end is studied, and the calculated results and quantities have been illustrated graphically in Fig.3 with p = 2, respectively. From Fig. 3, it is also detected that the parameters of the restraint stiffness have a significant influence on the critical buckling of the mosquito fascicle. Additionally, The results of our model affirm the critical role of lateral support in structural stability, corroborating well-known experimental outcomes by Jaiswal and Muthuswamy [7] and Kong and Wu [23]. The instability that occurs in a mosquito's fascicle in an attempt to penetrate the epidermis layer of human skin has been studied analytically. The impulsive forces applied by a mosquito to pierce the human skin create dynamic buckling in the fascicle. In conclusion, the presence of labium support improves the dynamic stability of the fascicle, increases Euler load and natural frequency, and also helps in achieving stable insertion.

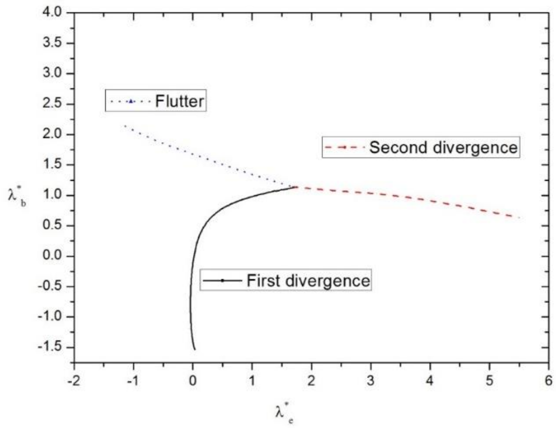

Fig. 4. Interaction stability curves between critical Beck and Euler loads.

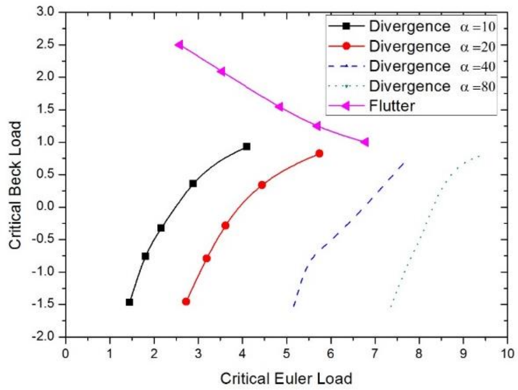

Fig. 5. Critical load pairs for non-zero lateral support and Beck load

Fig. 4 shows the interaction curves. The curves are identified as various zones; these zones have instability types, as shown by the first flutter, first divergence, and second divergence. The stability of a mosquito fascicle subjected to simultaneous Euler and Beck loads with and without the effect of labium support is investigated in this paper. It is shown that tensile Beck load has a tendency to destabilize the column, unlike the popular belief otherwise. However, the stability margins can be increased by applying compressive follower forces, which can be easily attained by using smart structure concepts. The coalescing point defines a pair of critical values for Beck and Euler loads. These critical load pairs are plotted. However, we evaluated the equation for different values of foundation stiffness by varying the parameter α to observe the effect on the critical load pairs. Fig. 5 shows the flutter and critical divergence pairs with α =0, i.e., no elastic foundation. Starting at zero Beck load and increasing that load to just below a value of 7, the Euler critical buckling load is raised before divergence instability occurs. This result is consistent with the results obtained by Rao and Singh. We have plotted the divergence instability criteria for different foundation stiffness and Beck loads. Fig. 5 shows a plot of the effect of non-zero α on the first divergence curve. As α is increased, the curves move toward higher values of Euler load. Increasing α does not shift the flutter curve. It simply raises the frequency of coalescence but the critical Beck/Euler pairs are not affected.

These collective research efforts not only shed light on the current state of knowledge in material and structural engineering but also pave the way for future innovations that draw inspiration from the natural world. The convergence of theoretical models, empirical studies, and bioinspired designs represents the frontier of modern engineering research, driving forward the development of materials and structures that are both advanced and aligned with natural principles. Overall, this research has the potential to impact multiple fields, ranging from healthcare and engineering to materials science and biotechnology, by providing innovative solutions and insights into the behavior of materials and structures.

Recent advancements in the mathematical modeling of biological structures, such as protein microtubules, have paved the way for significant biomedical innovations. The nonlocal elasticity approach has facilitated a more accurate understanding of vibrational behavior and thermal effects at the cellular level [39, 42]. Mahmoud et al. [43] demonstrated the role of shear deformation theories in predicting the dynamic buckling behavior of microtubules under axial loads. Similarly, the theoretical work of Ramady et al. [47, 48] introduced analytical models for rotational and thermal effects on piezoelectric materials, contributing to the design of resilient piezoelectric biosensors. These insights have found applications in the development of adaptive and precise medical devices, particularly microneedles and biomedical probes for targeted drug delivery [41, 44]. Additionally, Al-Solami et al. [45] developed a biomathematical model to optimize mosquito population control using sterile male technology, highlighting the versatility of mathematical approaches in biological research.

Emerging trends also reflect a growing interest in computational frameworks for modeling microbial and cellular processes. Bukhari et al. [46] proposed a neural network-based fractional-order model to simulate microbial diseases, offering valuable insights into pathogenesis and potential treatments for infections such as Buruli ulcer and cholera. The work of Taj et al. [39, 40] emphasized the impact of thermal stresses on the stability of microfilaments, showcasing the importance of orthotropic and Euler-based models in predicting structural integrity. Ghandourah et al. [49] further explored the mechanical stresses associated with avascular tumor growth, enhancing our understanding of biomechanical responses in cancer tissues. These comprehensive studies not only advance the theoretical understanding of biological structures but also inform the development of bioinspired engineering applications, including smart implants and wearable biosensors. This convergence of mathematical and computational models fosters interdisciplinary research, driving forward innovations in medical procedures and device design.

5. Conclusions

A mathematical approach has been developed to solve the buckling behavior of axially non-homogeneous mosquito fascicles with labium support, confirming the significant role of labium support as a non-conservative force. By applying the power series method, a characteristic polynomial equation for critical buckling loads was derived. The analysis demonstrated that an increase in the modulus of the foundation leads to a corresponding increase in the frequency of free vibration and the critical buckling load of the mosquito fascicle. Furthermore, comparisons with experimental results indicate that the power series method is both efficient and accurate for analyzing the buckling behavior of restrained mosquito fascicles.

These findings can inform the development of design strategies for creating dynamically stable, vibration-assisted microneedles for medical applications. It is also possible to explore alternative models that incorporate shear deformation and account for small-scale effects, such as the modified couple stress theory, to improve the accuracy of predictions. Additionally, similar methodologies could be adapted for the insertion of small, flexible medical devices into the brain or for the implantation of other complex medical instruments. This research paves the way for further innovations in medical procedures and device design, emphasizing the potential for bioinspired engineering solutions in healthcare.

Acknowledgment

This project was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, under grant No. (G: 470-130-1438). The authors, therefore, acknowledge with thanks DSR for technical and financial support.

References

[1] Alkenani, N., Mahmoud, S.R., Metwally, A.M., Alwabli, A.S., Al-Solami, H.M. "A mechanical approach for mosquito fascicle under the influence of mechanical forces with medical applications", *Struct. Eng. Mech., Int. J.*, Vol. 79, No. 6, pp. 677-682, (2021).

[2] Mahmoud, S.R., Al-Solami, H.M., Alkenani, N., Alhebshi, A., Alwabli, A.S., Bahieldin, A. "A mechanical model to investigate *Aedes aegypti* mosquito bite using new techniques and its applications", *Membr. Water Treat.*, Vol. 11, No. 6, pp. 399-406, (2020).

[3] Bhoyar, S., Varghese, V., Khalsa, L. "Thermoelastic large deflection bending analysis of elliptical plate resting on elastic foundations", *Waves Random Complex Media.*, 23 September, pp. 1-21, (2020).

[4] Bondla, S., Sharma, N., Panda, S.K., Hirwani, C.K., Mahmoud, S.R., Kumar, V. "Uncertain frequency responses of CNT–reinforced polymeric graded structure using fuzzified elastic properties–fuzzy finite element approach", *Waves Random Complex Media.*, 22 November, pp. 1-24, (2022).

[5] Mellal, F., Bennai, R., Nebab, M., Atmane, H.A., Bourada, F., Hussain, M., Tounsi, A. "Investigation on the effect of porosity on wave propagation in FGM plates resting on elastic foundations via a quasi-3D HSDT", *Waves Random Complex Media.*, 5 October, pp. 1-27, (2021).

[6] Bourada, F., Bousahla, A.A., Tounsi, A., Adda Bedia, E.A., Mahmoud, S.R., Benrahou, K.H., Tounsi, A. "Stability and dynamic analyses of SW-CNT reinforced concrete beam resting on elastic foundation", *Comput. Concr.*, Vol. 25, No. 6, pp. 485-495, (2020).

[7] Jaiswal, S., Muthuswamy, S. "Instability analysis of mosquito fascicle under compressive load with vibrations and microneedle design", *J. Bionic Eng.*, Vol. 12, No. 3, pp. 443-452, (2015).

[8] Zimmermann, S., Fienbork, D., Stoeber, B., Flounders, A.W., Liepmann, D. "Microneedle-based glucose monitor fabricated on a wafer-level using in-device enzyme immobilization", *Transducers '03: 12th Int. Conf. Solid-State Sensors, Actuators Microsystems*, Boston, MA, June 8–12, pp. 99-102, (2003).

[9] Gattiker, G.E., Kaler, K.V.I.S., Mintchev, M.P. "Electronic mosquito: designing a semi-invasive microsystem for blood sampling, analysis and drug delivery applications", *Microsyst. Technol.*, Vol. 12, pp. 44-51, (2005).

[10] Yang, M., Zahn, J. "Microneedle insertion force reduction using vibratory actuation", *Biomed. Microdevices*, Vol. 6, pp. 177-182, (2004).

[11] Qi, X., Song, W., Mao, Z., Gao, W., Cong, Q. "Fabrication of a bionic needle with both super-hydrophobic and antibacterial properties", *J. Bionic Eng.*, Vol. 10, pp. 377-382, (2013).

[12] Pailler-Mattei, C., Bec, S., Zahouani, H. "In vivo measurements of the elastic mechanical properties of human skin by indentation tests", *Med. Eng. Phys.*, Vol. 30, pp. 599-606, (2008).

[13] Yang, M., Zahn, J. "Microneedle insertion force reduction using vibratory actuation", *Biomed. Microdevices*, Vol. 6, pp. 177-182, (2004).

[14] Newton, A., Lal, A., Chen, X. "Ultrasonically driven microneedles", *NNUN REU Program at Cornell University*, pp. 34-35, (2003).

[15] Davis, S.P., Landis, B.J., Adams, Z.H. "Insertion of microneedles into skin: measurement and prediction of insertion force and needle fracture force", *J. Biomech.*, Vol. 37, pp. 1155-1163, (2004).

[16] Vincent, J.F.V., Wegst, U.G.K. "Design and mechanical properties of insect cuticle", *Arthropod Struct. Dev.*, Vol. 33, No. 3, pp. 187-199, (2004).

[17] Alwabli, A.S., Kaci, A., Bellifa, H., Bousahla, A.A., Tounsi, A., Alzahrani, D.A., Abulfaraj, A.A., Mahmoud, S.R., et al. "The nanoscale buckling properties of isolated protein microtubules based on modified strain gradient theory and a new single-variable trigonometric beam theory", *Adv. Nano Res.*, Vol. 10, No. 1, pp. 15-24, (2021).

[18] Bousahla, A.A., Bourada, F., Mahmoud, S.R., Tounsi, A., Algarni, A., Adda Bedia, E.A., Tounsi, A. "Buckling and dynamic behavior of the simply supported CNT-RC beams using an integral-first shear deformation theory", *Comput. Concr.*, Vol. 25, No. 2, pp. 155-166, (2020).

[19] Benmansour, D.L., Kaci, A., Bousahla, A.A., Heireche, H., Tounsi, A., Alwabli, A.S., Alhebshi, A.M., Al-ghmady, K., Mahmoud, S.R. "The nanoscale bending and dynamic properties of isolated protein microtubules based on modified strain gradient theory", *Adv. Nano Res.*, Vol. 7, No. 6, pp. 443-457, (2019).

[20] Ghandourah, E. "Nonlocal elasticity theory for the mechanical behavior of protein microtubules", *Phys. Mesomech.*, Vol. 24, No. 3, pp. 319-325, (2021).

[21] Sakes, A., Dodou, D., Breedveld, P. "Buckling prevention strategies in nature as inspiration for US instruments: a review", *Bioinspir. Biomim.*, Vol. 11, pp. 021001, (2016). DOI: 10.1088/1748-3190/11/2/021001.

[22] Barham, O.M. "A mathematical model for the mechanics of a mosquito bite with applications to microneedle design", *MS Thesis*, Department of Mechanical and Aerospace Engineering, NC State University, Raleigh, NC, (2007).

[23] Kong, X.Q., Wu, C.W. "Mosquito proboscis: An elegant biomicroelectromechanical system", *Phys. Rev. E*, Vol. 82, No. 1, pp. 011910, (2010).

[24] Ramasubramanian, M.K., Barham, O.M., Swaminathan, V. "Mechanics of a mosquito bite with applications to microneedle design", *Bioinsp. Biomim.*, Vol. 3, pp. 046001 (10pp), (2008). DOI: 10.1088/1748-3182/3/4/046001.

[25] Caddemi, S., Caliò, I., Cannizzaro, F. "Influence of an elastic end support on the dynamic stability of Beck's column with multiple weak sections", *Int. J. Nonlinear Mech.*, Vol. 69, pp. 14-28, (2015).

[26] Ferretti, M., Luongo, A. "Improving the linear stability of Beck's beam by added dashpots", *Int. J. Mech. Sci.*, Vol. 110, pp. 151-159, (2016).

[27] Rao, G.V., Singh, G. "A smart structures concept for the buckling load enhancement of columns", *Smart Mater. Struct.*, Vol. 10, pp. 843-845, (2001).

[28] Kurulay, M., Bayram, M. "A novel power series method for solving second-order partial differential equations", *Eur. J. Pure Appl. Math.*, Vol. 2, No. 2, pp. 268-277, (2009).

[29] Zerrouki, R., Karas, A., Zidour, M., Bousahla, A.A., Tounsi, A., Bourada, F., Tounsi, A., Benrahou, K.H., Mahmoud, S.R. "Effect of nonlinear FG-CNT distribution on mechanical properties of functionally graded nano-composite beam", *Struct. Eng. Mech.*, Vol. 78, No. 2, pp. 117-124, (2021).

[30] Wang, C.M., Wang, C.Y., Reddy, J.N. *Exact Solutions for Buckling of Structural Members*, CRC Press, LLC, Florida, (2005).

[31] Singh, K.V., Li, G.Q. "Buckling of functionally graded and elastically restrained non-uniform columns", *Composites B*, Vol. 40, pp. 393-403, (2009).

[32] Alhebshi, A.M., Metwally, A.M., Al-Basyouni, K.S., Mahmoud, S.R., Al-Solami, H.M., Alwabli, A.S. "Mechanical Behavior and Physical Properties of Protein Microtubules in Living Cells Using the Nonlocal Beam Theory", *Phys. Mesomech.*, Vol. 25, No. 2, pp. 181-186, (2022).

[33] Al-Basyouni, K.S., Mahmoud, S.R. "Mathematical approach for the effect of the rotation, the magnetic field and the initial stress in the non-homogeneous anelastic hollow cylinder", *Struct. Eng. Mech.*, Vol. 79, No. 5, pp. 593-599, (2021).

[34] Balubaid, M., Abdo, H., Ghandourah, E., Mahmoud, S. "Dynamical behavior of the orthotropic elastic material using an analytical solution", *Geomach. Eng.*, Vol. 25, pp. 331-339, (2021).

[35] Mahmoud, S.R., Alzahrani, E.O., Alzahrani, A.K., Ghandourah, E., Ghaleb, S.A. "Mathematical Model of Wave Propagation in Thermo-Magneto-Piezoelectric Transversely Isotropic Cylindrical Material", *J. Comput. Theor. Nanosci.*, Vol. 14, No. 8, pp. 3812-3820, (2017).

[36] Mahmoud, S.R., Alzahrani, E.O., Alzahrani, A.K., Ghandourah, E., Ghaleb, S.A. "Mathematical Model of Wave Propagation in Thermo-Magneto-Piezoelectric Elastic Solid Bar Immersed in an Inviscid Fluid", *J. Comput. Theor. Nanosci.*, Vol. 14, No. 8, pp. 3764-3771, (2017).

[37] Mahmoud, S.R., Ghaleb, S.A., Alzahrani, A.K. "Mathematical Model for Study the Microtubules Using Shear Deformation Theories", *Appl. Math. Sci.*, Vol. 11, No. 38, pp. 1871-1880, (2017).

[38] Shoffstall, A.J., Srinivasan, S., Willis, M., Stiller, A.M., Ecker, M., Voit, W.E., Pancrazio, J.J., Capadona, J.R. "A mosquito-inspired strategy to implant microprobes into the brain", *Sci. Rep.*, Vol. 8, No. 1, pp. 122, (2018).

[39] Taj, Muhammad, Mohamed A. Khadimallah, Muzamal Hussain, Khurram Fareed, Muhammad Safeer, Khaled Mohamed Khedher, Manzoor Ahmad, S. R. Mahmoud "Thermal stress effects on microtubules based on orthotropic model: Vibrational analysis." *Advances in Concrete Construction* 11, no. 3 (2021): 255-260.

[40] Taj, Muhammad, Mohamed A. Khadimallah, Muzamal Hussain, Shaid Mahmood, Muhammad Safeer, Yahya Rashid, Manzoor Ahmad, S. R. Mahmoud "Instability analysis of microfilaments with and without surface effects using Euler theory." *Advances in Nano Research* 10, no. 6 (2021): 509-516.

[41] Mahmoud, S. R., Shafeek A. Ghaleb, and A. K. Alzahrani. "Mathematical Model for Study the Microtubules Using Shear Deformation Theories." *Applied Mathematical Sciences* 11, no. 38 (2017): 1871-1880.

[42] S. R. Mahmoud, Shafeek A. Ghaleb, A. K. Alzahrani, E. Ghandourah "Mathematical approach of avascular tumor for effect of growth on the mechanical stresses", *Applied Mathematics and Information Science*, Vol. 11, No. 5, pp. 1353-1360, (2017).

[43] Al-Solami, Habeeb M., Alawiah MS Alhebshi, H. Abdo, S. R. Mahmoud, Afaf S. Alwabli, and Naser Alkenani. "A bio-mathematical approach to control the Anopheles mosquito using sterile males technology." *International Journal of Biomathematics* 15, no. 06 (2022): 2250037.

[44] Dhafer A. Alzahrani, Aala A. Abulfaraj, H.M. Mostafa, S.R. Mahmoud, Afaf S. Alwabli, Jabr Aljedani “Thermal Response of Protein Microtubules: A Nonlocal Elasticity Perspective on Cellular Mechanic” *Cattle Practice*, Vol. 32, no. 12, (2024).

[45] Afaf S. Alwabli, Ghadeer Bukhari, Mohammed Balubaid, Mohammed Tarique, S. R. Mahmoud, Jabr Aljedani, Ahmed Ramady, “Analyzing Thermal Influences on Protein Microtubules in Eukaryotic Cells through Nonlocal Elasticity Modeling” *Cattle Practice*, Vol. 32, no. 12, (2024).

[46] Ghadeer Bukhari, Afaf S. Alwabli, S.I. Ali, Jabr Aljedani, Ahmed Ramady, S. R. Mahmoud, “A Computational Neural Network Framework for Fractional-Order Modeling of Buruli Ulcer and Cholera: Insights into Microbial Genetics and Pathogenesis” *Cattle Practice*, Vol. 32, no. 12, (2024).

[47] Ramady, Ahmed, S. R. Mahmoud, and H. A. Atia. "A theoretical approach in 2D-space with applications of the periodic wave solutions in the elastic body." *Membrane Water Treatment* 11, no. 4 (2020): 295-302.

[48] Ramady, A., Atia, H.A., and Mahmoud, S.R. "An analytical solution for equations and the dynamical behavior of the orthotropic elastic material." *Advances in Concrete Construction* 11, no. 4 (2021): 315-321.

[49] Ramady, Ahmed, B. Dakhel, Mohammed Balubaid, and S. R. Mahmoud. "A mathematical approach for the effect of the rotation on thermal stresses in the piezo-electric homogeneous material." *Computers and Concrete* 25, no. 5 (2020): 471-478.