

Article

Investigating Mechanical Response and Structural Integrity of Tubercle Leading Edge under Static Loads

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Abstract: This investigation into the aerodynamic efficiency and structural integrity of tubercle leading edges, inspired by the agile maneuverability of humpback whales, employs a multifaceted experimental and computational approach. By utilizing static load extensometer testing complemented by computational simulations, this study quantitatively assesses the impacts of unique wing geometries on aerodynamic forces and structural behavior. The experimental setup, involving a Wheatstone full-bridge circuit, measures the strain responses of tubercle-configured leading edges under static loads. These measured strains are converted into stress values through Hooke's law, revealing a consistent linear relationship between the applied loads and induced strains, thereby validating the structural robustness. The experimental results indicate a linear strain increase with load application, demonstrating strain values ranging from 65 $\mu\epsilon$ under a load of 584 g to 249 $\mu\epsilon$ under a load of 2122 g. These findings confirm the structural integrity of the designs across varying load conditions. Discrepancies noted between the experimental data and simulation outputs, however, underscore the effects of 3D printing imperfections on the structural analysis. Despite these manufacturing challenges, the results endorse the tubercle leading edges' capacity to enhance aerodynamic performance and structural resilience. This study enriches the understanding of bio-inspired aerodynamic designs and supports their potential in practical fluid mechanics applications, suggesting directions for future research on manufacturing optimizations.

Keywords: strain; stress; extensometer; tubercle leading edge; structural analysis

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1. Introduction

1.1. Background

Humpback whales, despite their immense size and weight, appear to effortlessly navigate their environment with remarkable agility and precision. Unlike what one might expect, these majestic creatures dart through the water with swift and graceful movements, executing intricate U-shaped trajectories with remarkable curvature while on the hunt [1]. Central to their exceptional maneuverability are the finely tuned mechanisms within their pectoral flippers [2], which serve as their primary means of controlling posture and direction. Among the distinctive features of humpback whale flippers are peculiar serrations along their leading edges, believed to be instrumental in optimizing their hydrodynamic performance [3–5]. In the context of advancing aerodynamic designs, this study delves into the application of tubercle leading edges, a concept inspired by the natural adaptations seen in humpback whale flippers. Tubercle leading edges incorporate a series of systematic bumps or protuberances along the leading edge of a wing. These features disrupt airflow in a manner that enhances lift and delays the onset of stall at higher angles of attack, crucial for maintaining stability and efficiency in fluid mechanics applications. To clarify,

by modifying pressure distribution and delaying flow separation, tubercle leading edges maintain lift at angles that would cause stall in straight wings. This feature is particularly advantageous for aircraft operating in diverse atmospheric conditions, potentially extending the operational envelope and improving fuel efficiency. The distinctive geometry of these edges is pivotal for studying their influence on aerodynamic performance and structural integrity under varying conditions [6–9].

The aeronautical community's fascination with sinusoidal leading-edge wings is fueled by compelling experimental findings indicating that the unique shape of the leading edge profoundly influences the stall mechanism. This interest has been piqued by a growing body of evidence suggesting that the incorporation of sinusoidal leading edges has the potential to revolutionize aerodynamic performance and stall behavior [10,11], deep stall [9], and dynamic stall [12–14]. Rather than experiencing a sharp decline in performance concentrated at a specific angle of attack, the stall phenomenon is mitigated across a significantly broader range, thereby circumventing the typical abrupt loss of lift [15–17]. In certain instances, stall is even altogether eliminated, allowing for nearly constant performance enhancements as the wing's angle of incidence is increased.

Miklosovic et al. [18], conducted experimental trials on sinusoidal leading-edge wings, and their findings revealed that wings with larger amplitudes exhibited a more gradual stall pattern, attributed to stalls occurring later in the regions behind the peaks compared to those behind the troughs. Other scholars validated this through an experimental and numerical investigation of a rectangular wing incorporating the Wavy Leading Edge effect, demonstrating improved lift force during pitching motion with minimized stall [19–21], suggesting potential applications in wind turbines [22–24]. The experimental investigation performed by N. Karthikeyan et al. [25,26] examined the impact of wavy leading edges, revealing tubercles' effectiveness in maintaining attached flow and reducing recirculating zones, although their influence on separation point variability and wake width post-stall requires further exploration. However, Jabbari et al. [27], by employing static roughness elements, significantly improved the performance of these unconventional wing configurations. The aerodynamic performance of varying leading-edge tubercle configurations was numerically [28,29] and experimentally [30] evaluated, indicating that a larger tubercle amplitude leads to gentler stall, while a smaller tubercle wavelength improves maximum lift. The application of this distinctive feature has recently extended into the realm of water turbine design [31–33].

Since the 1980s, a plethora of studies have delved into the structure and characteristics of humpback whale pectoral flippers [6,31,34]. Nonetheless, a comprehensive understanding regarding the distribution of strain and stress across these surfaces remains elusive.

1.2. Research Objective

Building upon prior research on wing aerodynamics, structural mechanics, and experimental techniques, this paper embarks on a rigorous exploration of extensometer testing, as applied to sinusoidal leading-edge wings. By integrating findings from the existing literature with the experimental results, this article aims to offer a nuanced understanding of the intricate mechanisms governing the behavior of this novel wing configuration. Through this interdisciplinary approach, this paper aspires to enrich the body of knowledge surrounding innovative wing designs and pave the way for future advancements in aerospace engineering.

In this paper, a comprehensive investigation into the extensometer testing of a sinusoidal leading-edge wing is presented, aiming to elucidate its structural response characteristics under aerodynamic loading. Through meticulous experimentation and analysis, the paper seeks to unravel the intricate interplay between the wing's unique geometry, aerodynamic forces, and structural integrity. This study not only contributes to advancing the understanding of sinusoidal leading-edge wing performance, but also provides valuable insights into the broader domain of unconventional wing design and testing methodologies. To acquire the determined aims, the wing was mounted on the wind tunnel and then four

strain gages were installed on the surfaces, two of them outside and two others inside the wing. Strain gages were connected to the strain indicator, and they took part in a Wheatstone bridge. Each strain gauge was considered as a resistance in the bridge, and the variation in the resistance was measured by the indicator. In the next step, the strain on the wing surface was numerically calculated and the computational results were compared with the experimental ones.

1.3. Significance of Study

The quest for enhancing aerodynamic performance and structural integrity in aerial shapes, such as the blades of wind turbines, has led to the exploration of innovative blade designs. Among these, the sinusoidal leading-edge wing stands out as a promising candidate, characterized by its unique sinusoidal shape, which offers potential improvements in lift generation and stall resistance. As researchers delve deeper into understanding the aerodynamic behavior and structural responses of such unconventional wing configurations, experimental methods play a pivotal role in providing empirical insights.

Extensometer testing emerges as a fundamental experimental technique employed in the evaluation of structural deformations and material properties under various loading conditions. This technique, rooted in the principles of strain measurement, offers a detailed analysis of the deformation behavior experienced by a wing structure subjected to aerodynamic forces. By precisely quantifying the strain distribution along the wing's surface, extensometer testing facilitates the assessment of structural performance and aids in the validation of computational models.

In applications where minimizing energy consumption is critical, passive flow control can be the optimum choice. It is claimed that this type of nature-inspired wing can overcome the problems associated with early flow separation and stall in low-speed flights by generating a sufficiently high lift to drag ratio. As elucidated earlier, the aerodynamic efficacy of wind turbine blades is linked to the overall weight of the system. While integrating lighter materials into the system can lead to weight reduction, it is imperative to ensure that this does not compromise the structural integrity. Moreover, investigating structural integrity becomes paramount in fixed designs to assess the blade performance under standard loads, where adaptability is not a factor. The adoption of a sinusoidal leading-edge design, inspired by the remarkable efficiency observed in humpback whale flippers, has emerged as a promising passive flow control method. Consequently, conducting a static test on the wing serves as a vital step in ensuring the safety and reliability of the structure.

2. Experimental Setup

This study adopts a robust multidisciplinary approach, synthesizing expertise from mechanical engineering, materials science, and fluid dynamics to comprehensively investigate the aerodynamic and structural performance of tubercle leading-edge designs. This integration facilitates a holistic understanding of how unique wing geometries influence airflow and structural stability. By combining computational fluid dynamics simulations with empirical experimental data, the research elucidates the interaction between aerodynamic forces and material responses. Theoretical models predict airflow patterns and stress distributions, which are validated through physical testing to ensure the accuracy and reliability of the results. This approach not only enriches the analysis, but also verifies the practical applicability of tubercle leading edges in enhancing aerodynamic efficiency and structural durability.

As previously noted, the wing was affixed within a wind tunnel equipped with four strain gauges. The applied load surpassed normal operational thresholds to ensure safety, with loads strategically positioned along the wing span to replicate distributed loads like pressure distribution. The primary material employed in constructing the wing was thermoformed ABS polymer, with Table 1 delineating its characteristics. The wing fabrication process was carried out at IST University, utilizing a medium-sized 3D printer

boasting a working field spanning from 200 to 250 mm in the X and Y directions. Leveraging a 3D printer enhanced both the precision and efficiency of wing production.

Table 1. Mechanical properties of ABS.

Density ($\frac{\text{kg}}{\text{m}^3}$)	Poisson Ratio	Young Modulus (Pa)
1020	0.394	8.92×10^8

The following sections discuss, in detail, the adopted wing design in terms of the effective geometric parameters and construction procedure, as well as the method of deformation assessment.

2.1. Structural Properties

The models were originally constructed using the CAD software SOLIDWORKS 2015 sp5.0, based on a prescribed wing section. The airfoil NASA LS (1)-0417 was chosen for this purpose, because it is characterized by a large leading edge radius, thus resulting in a more predictable stall [35].

To check the data, a graphic plot was drawn, and Figure 1 clearly depicts these data. Moreover, the mass center of the airfoil was found and it is shown in this picture. The center of mass was obtained for the airfoil and the point was (0.4248chord (c), 0.0183c).

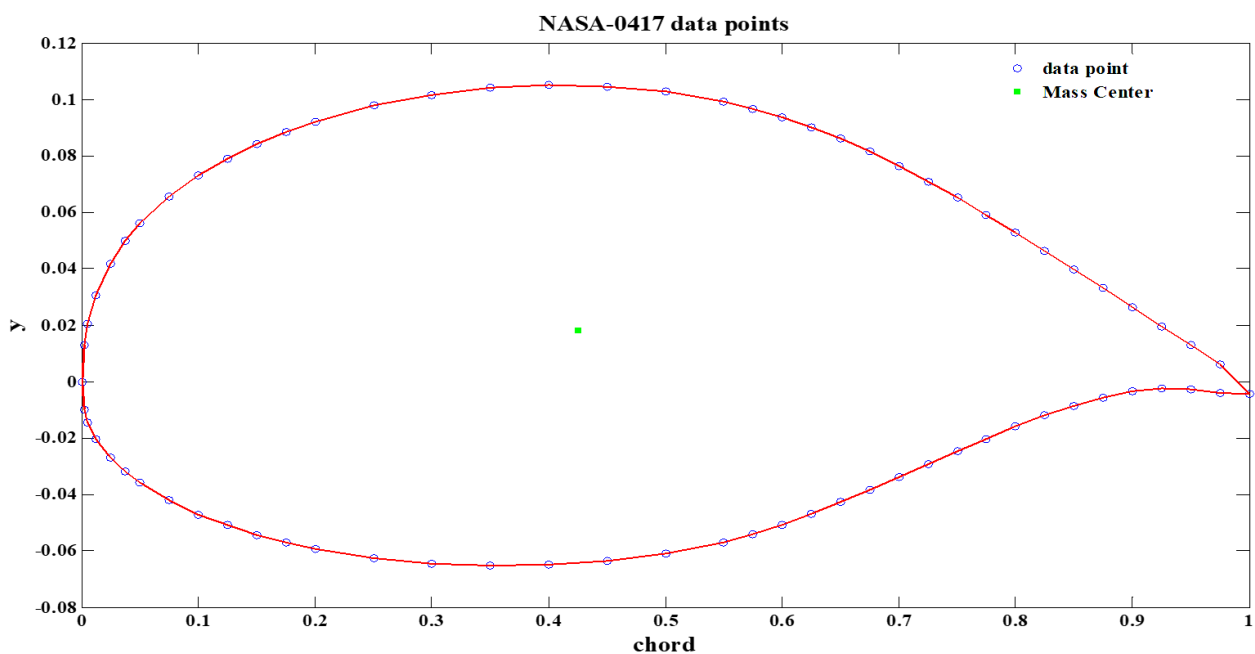


Figure 1. Plot of data point of NASA-0417 airfoil and coordinates of the mass center of it.

In order to generate the sinusoidal leading edge, the reference wing section had to be modified without distorting the trailing region. It was decided that the original airfoil should correspond to zero amplitude points in the sinus wave. Hence, the profiles located at smaller chord zones than the reference (valleys) had a larger leading edge radius and the profiles corresponding to maximum amplitude zones, displaying larger chords (peaks), were relatively thinner than the reference geometry and had a smaller leading edge radius. The mean chord of all the models used in the present study was kept constant. In previous studies, various values of the amplitude-to-chord ratio A/c and wavelength-to-chord ratio λ/c of the wave (see Figure 2) were studied to account for their effect [36,37].

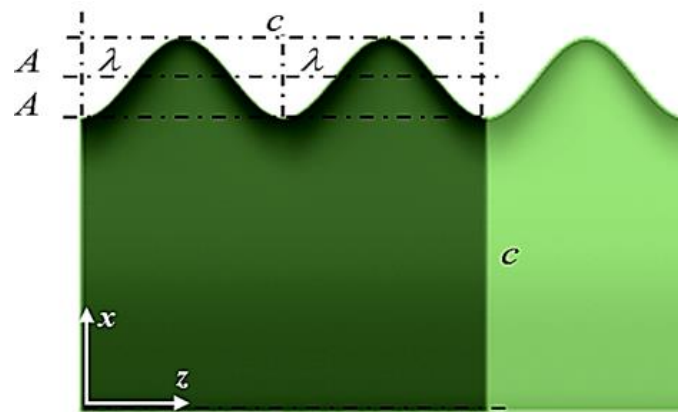


Figure 2. Geometric definition of the planform of the sinusoidal leading edge wing models.

The sinusoidal leading-edge wing was constructed, and this equation was applied to generate the surface of the wing:

$$x = A \sin\left(2\pi\left(\frac{z}{\lambda} - \frac{\lambda}{2}\right)\right) \quad (1)$$

where A , λ , and z are the amplitude and wavelength of the leading edge and the length of the span, respectively. The profiles located at smaller chord zones than the reference (troughs) exhibited a larger leading-edge radius and the profiles corresponding to the maximum amplitude zones, displaying larger chords (peaks), were relatively thinner than the reference geometry and showed a smaller leading-edge radius. Naturally, the mean chord of all the models used in the present study was kept constant. In addition, square wing tips were selected in order to avoid the addition of extra variables to the design of the models.

However, λ/c and A/c were fixed to 0.12 and 0.5 in this present work, respectively, and the AR (aspect ratio) was equal 1.5. Table 2 summarizes the variations considered for finite wing simulations, with model B corresponding to the clean (baseline) geometry and models S3 and S4 to sinusoidal geometries with different numerical aspect ratios. As a result, the wing ended abruptly, but this option has the advantage of avoiding the addition of extra variables to the design of the models. The perspectives of three wings are also depicted in Figure 3.

Table 2. Specifications of the models used in infinite wing simulations.

Model	AR	Centerline	A/c	λ/c
B	1.5	-	-	-
S3	1	valley	0.12c	0.5c
S4	1.5	peak	0.12c	0.5c

The small dimensions of the 3D printer box require that the maximum span of a model must be less than 200 mm to ensure that it does not undergo bending during construction. Therefore, the model was constructed in two parts to reduce the span. To allow for the installation of the accelerometers inside the wing, one plate in each part of the wing was added in the lower camber. Another limitation of the printer is that it cannot construct bodies with a thickness less than 2 mm.

The two parts were glued with araldite and the plates were fitted and could be easily removed. Rubber was used to fill the empty spaces between the plates and wing. The entire model had a total mass of 470 g. Figure 4 illustrates a part of the model constructed by the 3D printer.

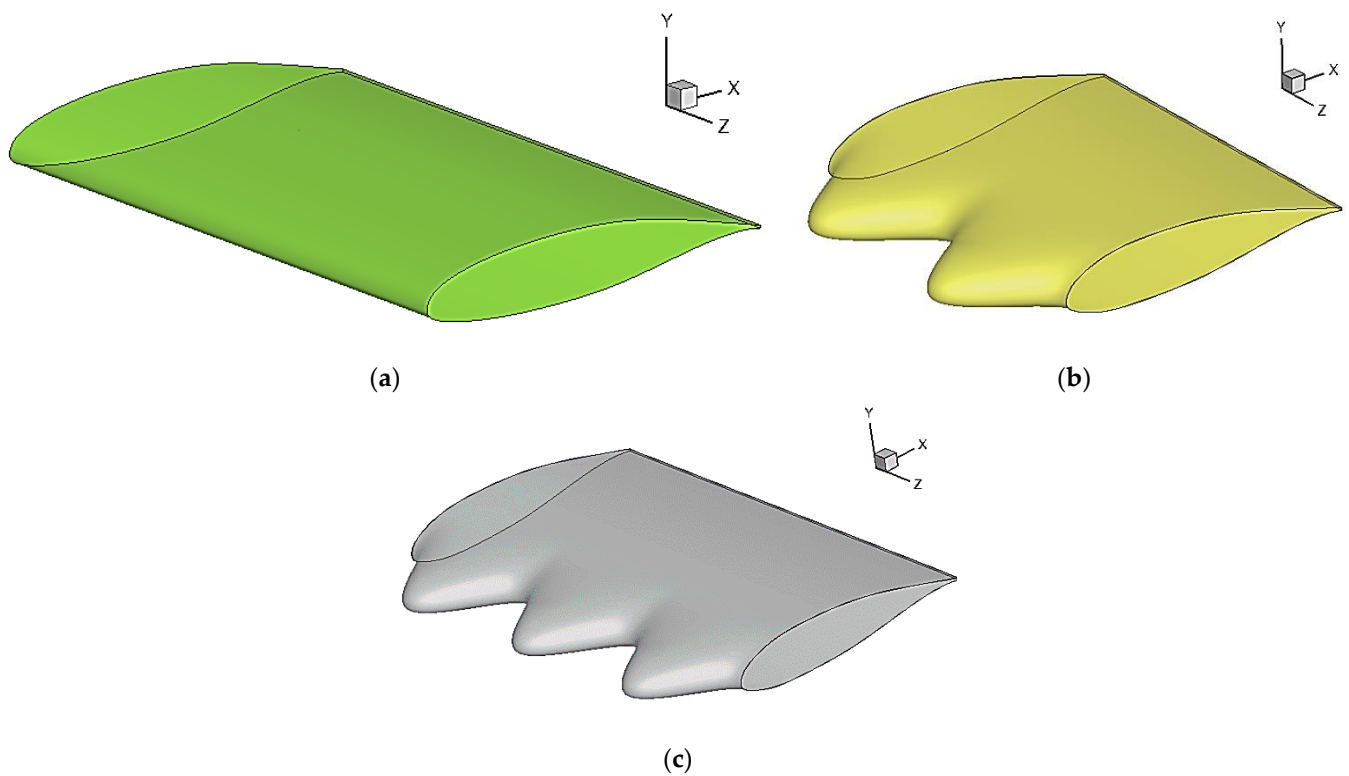


Figure 3. Perspective of (a) base wing, (b) S3, and (c) S4.

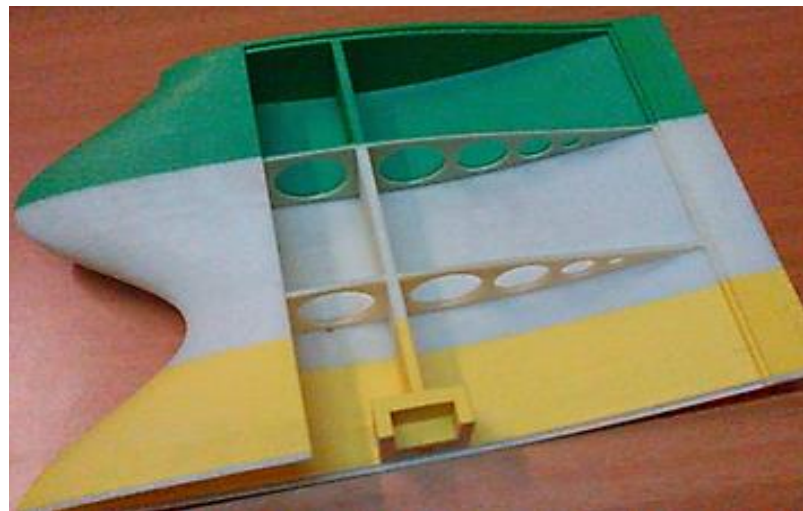


Figure 4. Part of the model.

Furthermore, the present experimental measurements rely on the precise quantification of mechanical strain using a Wheatstone full-bridge circuit. This electrical circuit configuration is critical for accurately determining minute changes in resistance caused by mechanical strain on aerodynamic surfaces. Comprising four interconnected strain gauges, the circuit effectively balanced two legs of a bridge, one of which contained the test sample. Changes in resistance, induced by mechanical deformation (strain), were converted into measurable electrical signals. This setup is essential for confirming theoretical models with empirical data, thereby providing a robust basis for evaluating the performance of the tubercle leading edges under applied static loads.

2.2. Strain Measurement Method

The extensometer study focuses on the length change measurements and is useful for stress–strain measurements and tensile tests. There are two main types of extensometers: contact and non-contact. For certain special applications where it is impractical to use a feeler arm or contact extensometer, non-contact extensometers are beginning to bring advantages, and laser and video extensometers are two typical types of this. Otherwise, contact extensometers are used and one of the important components applied in contact tests is strain gauges.

The specimen extension was transmitted via sensor arms to the mechanical portion(s) fitted with strain gauges, causing a defined deformation of the strain gauges, as shown in Figure 5. The standard resistance of 120 ohms was chosen because of the balance of several points, such as optimal performance, efficient power consumption, and suitability with many strain indicators, including with battery-powered or portable ones. The portable strain indicator used in this study, Vishay Measurements P-3500 Portable Strain Indicator, works with a variety of strain gauges, but 120 ohms is often preferred for its lower power requirements and good signal output, especially in the case of portable systems.

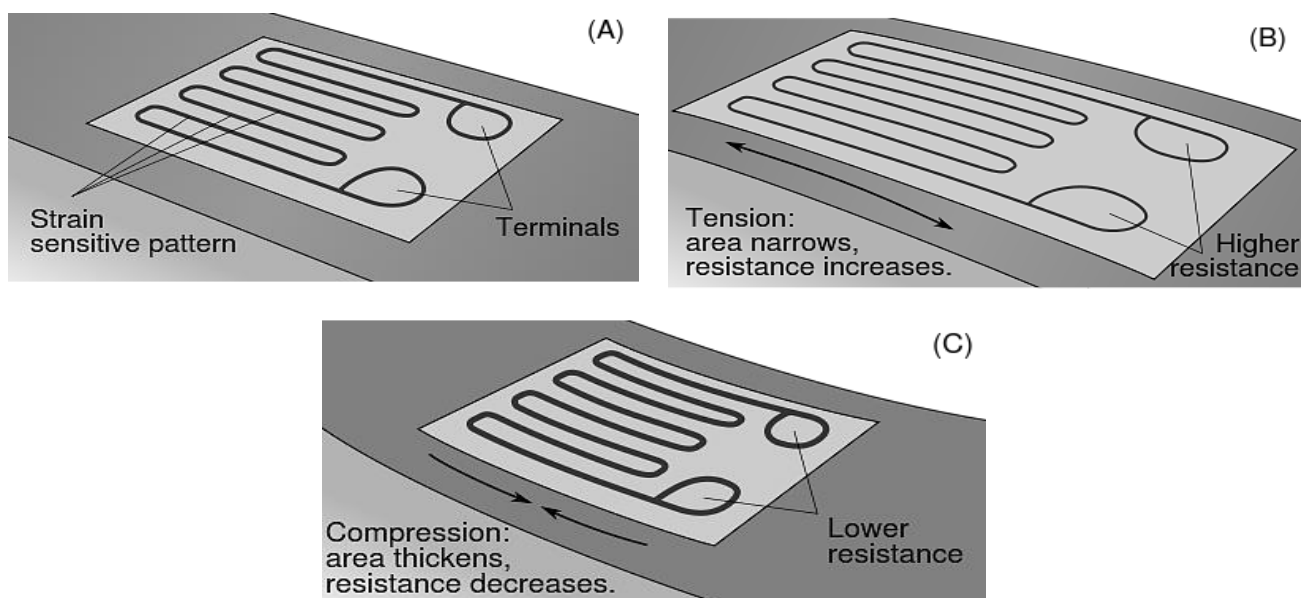


Figure 5. Visualization of the working concept behind the strain gauge on a beam under exaggerated bending [36].

The strain gauge length was approximately 10 mm, which is appropriate for the strain measurement of specific medium-sized aircraft or automotive components. For detailed and precise applications, shorter gauges are preferable, whereas for broader structural health monitoring, longer gauges are more suitable.

While the experiment was performed in an environmentally controlled condition, the basic thermal compensation method can serve as a protection against slight thermal effects and potential errors. However, utilizing a full-bridge strain gauge configuration is an excellent approach to minimizing the effects of temperature changes on strain measurements. This configuration maximizes sensitivity to strain while simultaneously minimizing unwanted signals from temperature changes.

This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor. It is commonly known that the strain gauge transforms the strain applied into a proportional change in resistance. The

relationship between the applied strain $\varepsilon (\varepsilon = \frac{\Delta L}{L_0})$ and the relative change in the resistance of a strain gauge is described by the following equation:

$$\frac{\Delta R}{R_0} = k \cdot \varepsilon \quad (2)$$

The factor k , also known as the gauge factor, is a characteristic of the strain gauge and the exact value is specified on each strain gage package. In general, the gauge factor for metal strain gauges is about 2.

In the Wheatstone bridge and for the sake of clarity, it is more convenient to consider the ratio of the output and the input voltage U_A/U_E . Therefore, the following equations are set up for the ratio:

$$\frac{U_A}{U_E} = \frac{R_1 \cdot R_3 - R_2 \cdot R_4}{(R_1 + R_2)(R_3 + R_4)} \quad (3)$$

if the resistors R_1 to R_4 vary, the bridge will be detuned and an output voltage U_A will appear. With the additional assumption that the resistance variation is much smaller than the resistance itself (which is always true for metal strain gauges), second-order factors can be disregarded. Then, the following equation is obtained:

$$\frac{U_A}{U_E} = \frac{1}{4} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \quad (4)$$

By substituting Equation (2) in (4), it is given as

$$\frac{U_A}{U_E} = \frac{k}{4} \cdot (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \quad (5)$$

3. Result and Discussion

Figure 6 depicts the wing mounted within the setup, with weights suspended on either side for experimental purposes. The loading figures were selected to estimate the real-world aerodynamic forces, such as the maximum weight or lift at around 1 Kg on each side. This magnitude also allowed for studying the structure's behavior and incorporated material's properties. The locations where large stresses were anticipated under typical operating conditions or points where aerodynamic forces had a large impact were considered to apply the forces. As illustrated in Figures 6 and 7, the leading edge at the wing tip was chosen as a point for the mentioned assessment. Placing the weights at peaks and troughs would help to consider the specific geometric effects that the sinusoidal leading edge might have had on the stress distribution. Therefore, the weights were placed close to the peaks at the leading edge to capture the distribution of load across the wing.

Four strain gauges, configured in full-bridge arrangements, as previously described, were affixed to both the surface and spar of the wing. As illustrated in the subsequent figure, one strain gauge was positioned on the spar, while another was placed in the same location but on the outer surface (Figure 7a). The remaining two strain gauges were situated at corresponding positions, both internally and externally, along the skin of the wing (Figure 7b). It is worth noting that ensuring the precise geometric alignment of strain gauge pairs was imperative. Thus, the exact positions of the strain gauges were meticulously determined prior to affixing each pair to their respective mirror image locations. One pair, as illustrated in the Figure 7a, was positioned on the spar, close to the position of the hanging loads, to assess the structural integrity under bending loading. This location was predicted to experience a higher stress value and was more susceptible to structural damage compared to the other parts of the spar. The other paired strain gauges were attached to the upper skin of the wing structure, inside and outside, since the wing's skin is known to be prone to fatigue or dynamic stress and is the first component of the wing to experience the tension under bending loading. Thus, the measurement of the tensile strain on the upper surface of the wing, as well as the bended spar, must be the area of interest.



Figure 6. The mounted wing setup and hanging weights.

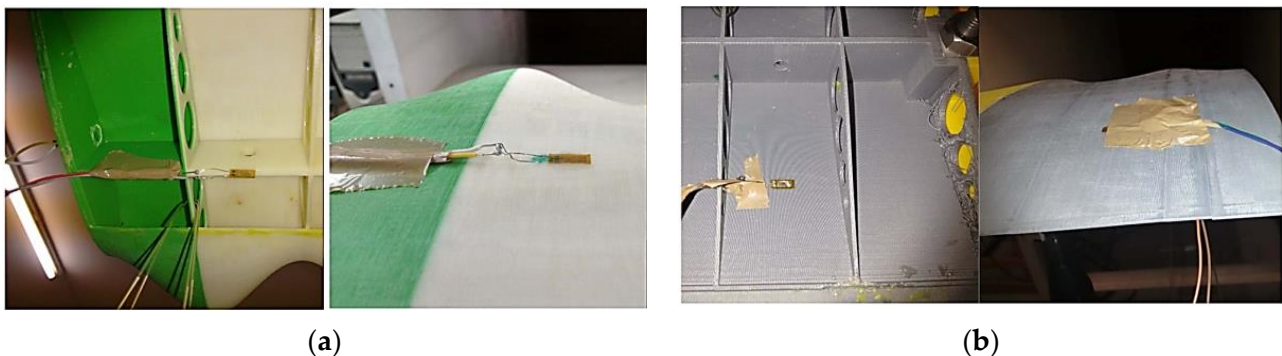


Figure 7. Four strain gauges installed on the wing, inside and outside.

The experimental setup was carefully engineered to mimic realistic aerodynamic conditions, enabling precise measurements of the tubercle leading edge's performance under varied loading scenarios. Central to the present experimental methodology was a state-of-the-art wind tunnel, equipped with advanced instrumentation to measure the aerodynamic forces and structural responses. The wings, fabricated using high-precision 3D printing techniques, were outfitted with an array of strain gauges, integrated into a Wheatstone full-bridge circuit for optimal sensitivity and accuracy. These gauges recorded minute deformations in response to controlled airflow conditions ranging from gentle breezes to high-velocity winds, simulating different flight environments. This setup not only allowed for the detailed mapping of strain and stress, but also facilitated a comparative analysis between the computed predictions and empirical data, thereby providing a robust framework for assessing the efficacy of tubercle leading-edge configurations in real-world applications.

Subsequently, all the strain gauges were linked to the "Switch and Balance Unit" in the configuration of full-bridge Wheatstone circuits. This unit comprised 10 channels, with each channel corresponding to a designated input and output pathway. In instances involving multiple sensors or inputs, the unit systematically processed the input data and delivered outputs through the respective output channels. These channels are commonly interfaced with a data monitoring system. Figure 8 depicts the utilized Switch and Balance

Unit alongside the strain indicator during the experiment, with the tenth channel being visibly utilized.

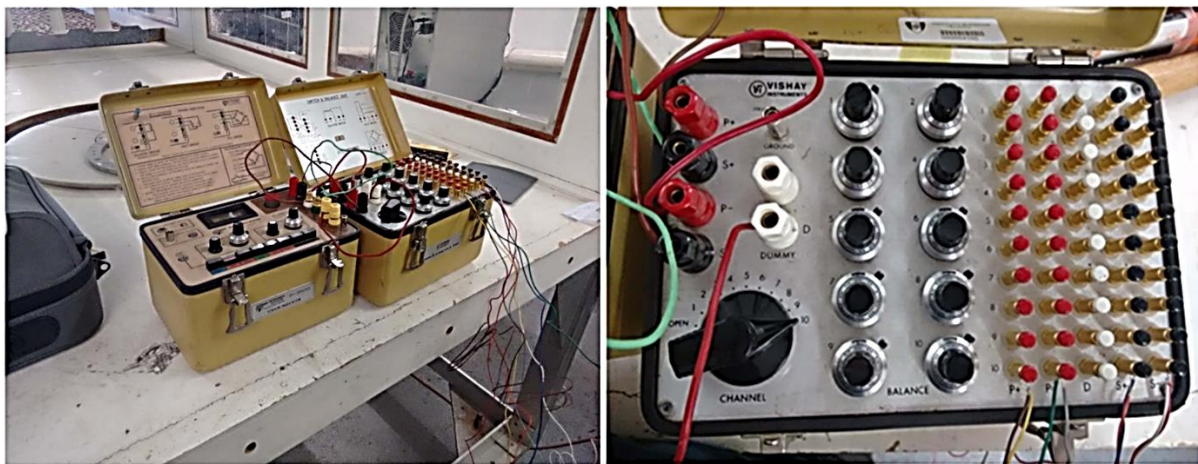


Figure 8. Strain indicator connected to Switch and balance Unit (left) to Switch and balance Unit (right).

As previously mentioned, the recorded strain served as a crucial input for calculating the corresponding stress using Hooke's law. The resulting strain measurements and the corresponding stress values are presented in Table 3 for reference.

Table 3. Strain measured in experimental test and calculated stress by Hooke's law.

Weight (g)	Strain (Micron) ($\mu\epsilon$)	Stress (KPa)
584	65	57.954
712	75	66.87
828	89	79.3524
1168	130	115.908
1344	149	132.8484
1528	177	157.8132
1692	202	180.1032
1916	231	205.9596
2122	249	222.0084

The experimental results derived from the static load tests on the sinusoidal leading edge, as presented in Table 3, revealed a consistent linear relationship between the applied load and the resultant strain and stress, adhering to Hooke's law within the material's elastic limit. The data suggest that the wing's material and structural configuration exhibited predictable and stable mechanical properties under the range of the static loads tested. The linear progression of strain with an increasing load indicates that the leading-edge design maintained its structural integrity without reaching the yield point. This elastic behavior is fundamental for blades, which require a balance between strength and flexibility to accommodate aerodynamic forces during operation.

Experimental and Numerical Correlation

The successful capture of material response through extensometer-based strain gauges signifies a methodologically robust approach, offering detailed insights into stress distribution and highlighting the uniformity of material behavior across the blade span. Figure 9 depicts the resultant strain from the numerical analysis performed in ANSYS commercial software 15.02. The whole procedure, including the boundary conditions and selected dimensions, was chosen to be similar to the experimental setup, and the results are compared in Figure 10.

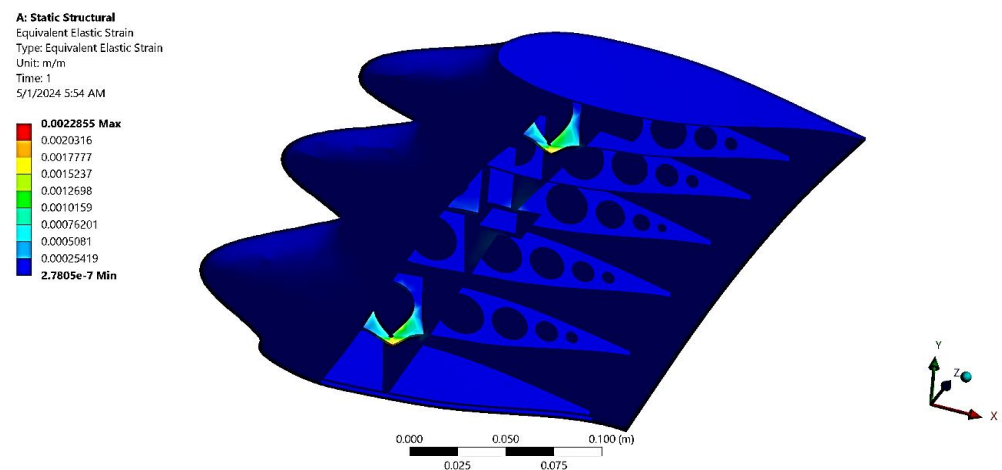


Figure 9. Obtained numerical strain for experimental results' validation.

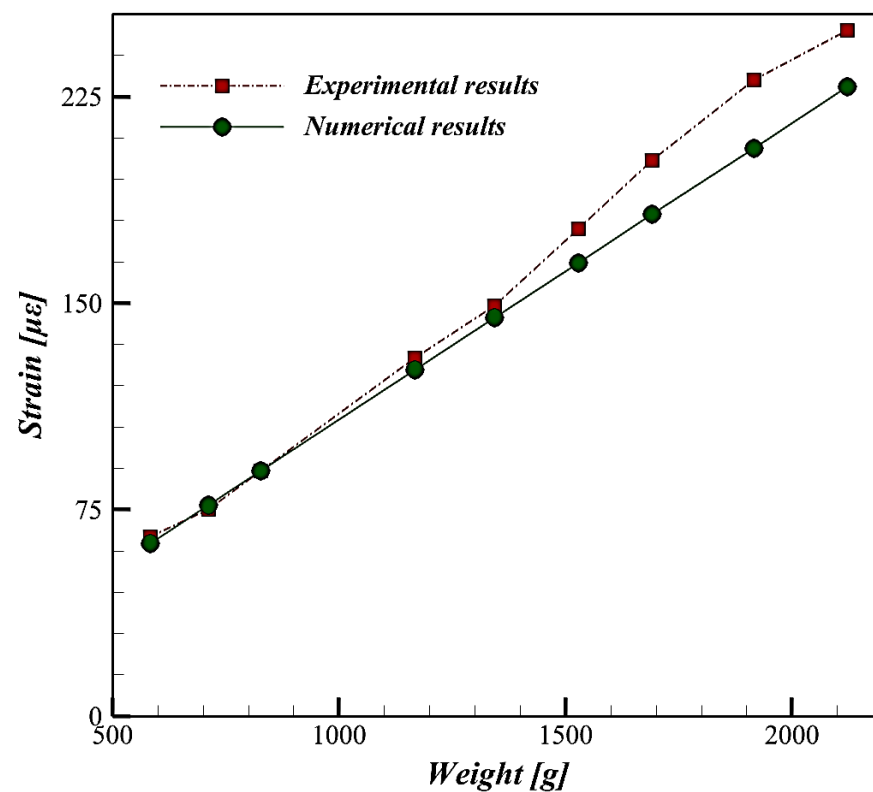


Figure 10. Experimentally obtained values for elastic strain versus the applied load and corresponding numerical figures.

The congruence of these values corroborates the reliability of the computational model, which can be instrumental in predicting a blade's response to varying loads, thus facilitating the design optimization process without extensive physical testing. Clearly, ribs that directly experienced the applied loads from weights, exaggeratedly deformed, demonstrated larger strain levels, which indicates the susceptibility of the region to any possible structural damage. This visualization can help with the optimization of the material, geometry, and regions of load application to improve structural integrity and performance.

The application of tubercle leading-edge modifications, inspired by bio-mimetic principles, is hypothesized to enhance aerodynamic performance. However, these modifications must not compromise structural integrity. The present data confirm that the incorporation of tubercles does not adversely affect the material's response to static loads. This suggests

that the tubercle enhancement potentially provides an aerodynamic advantage without a structural penalty, and without the need for iterative testing for geometry optimization purposes, supporting the hypothesis that biomimetic structures can be integrated into blades' design effectively.

The linear relationship between the strain and applied load may suggest minimal deformation within the wing structure. Nevertheless, to facilitate a comprehensive comparison, numerical strain values were juxtaposed with the experimentally obtained figures, as illustrated in Figure 10. Notably, the experimental strain readings closely aligned with the numerical predictions when the applied weights were below 1400 g. However, as the weight increased, the experimental strains exhibited a slight deviation towards higher values. This discrepancy may have stemmed from inherent defects introduced during the printing process, potentially leading to more pronounced deformations within the system. This result can be attributed to many reasons, including the imprecision of the ABS material properties (elastic modulus), mesh resolution of the numerical model, experimentally applied boundary condition for loads, and inevitable defects in the produced structure such as voids.

Considering that the initial portions of the numerical and experimental strains aligned considerably, it can be concluded that the incorporated materials in both methods did not differ significantly in terms of their mechanical properties. In other words, the material properties, including Young's modulus and other critical mechanical properties, were validated in the both measurement methods. This process improved the reliability of the model for predicting the behavior of the wing under real operating conditions while ensuring safety and an optimal performance under the assumed aerodynamic loading condition. However, heavier loads can reveal structural defects. The mechanical behavior of printed structures depends on various factors, such as the printing temperature, nozzle diameter, printing direction, and in-fill density.

Even with a nozzle temperature between 230 and 260 °C, 100% fill-density in thickness, bed temperature around 100 °C, and filament's width to thickness ratio of 0.25, there is still a possibility of micro-size intra-bead void formation [38], which can significantly affect the mechanical response, leading to faster plasticity formation [38]. Poor adhesion between adjacent filaments due to an inappropriate printing temperature can weaken the structure, particularly when the loading direction is perpendicular to the printing direction.

The optimum printing parameters were chosen to minimize the occurrence of defects, but the presence of an inhomogeneous surface or micro-empty spaces between the printed filaments in the wing's interior can cause deviation in the strain curve during experimental analysis. Despite this, under the loading conditions applied in this study, such deviations can be considered as negligible. However, larger strains associated with experimental tests can markedly reduce the mechanical properties of the structure, including its strength, especially under intense dynamic loads.

The observed trend in the stress versus strain variations indicated that the applied load did not induce plasticity or permanent deformation within the wing. However, prolonged exposure to such deformations could potentially lead to fatigue, thereby impacting the lifespan of the wing. Clearly, if the static load in this analysis was applied in a cyclic sinusoidal pattern, it would be possible to find the number of cycles that the wing could tolerate under such deformation.

In practical conditions, wings are subjected to a myriad of cyclic loading scenarios. Understanding the repercussions of cyclic loading is paramount to ensuring structural integrity under various service and loading conditions.

To this end, the loading in this test was treated as cyclic, with a stress amplitude of 2.22 MPa and a stress ratio ($R = -1$). The stress amplitude represents half the difference between the maximum and minimum stress within a cycle. To estimate the fatigue life of the wing, the material's fatigue life under comparable conditions was referenced, typically obtained from standardized fatigue tests, resulting in the S-N curve (Wöhler curve) for the ABS material utilized in the experiment as shown in Figure 11.

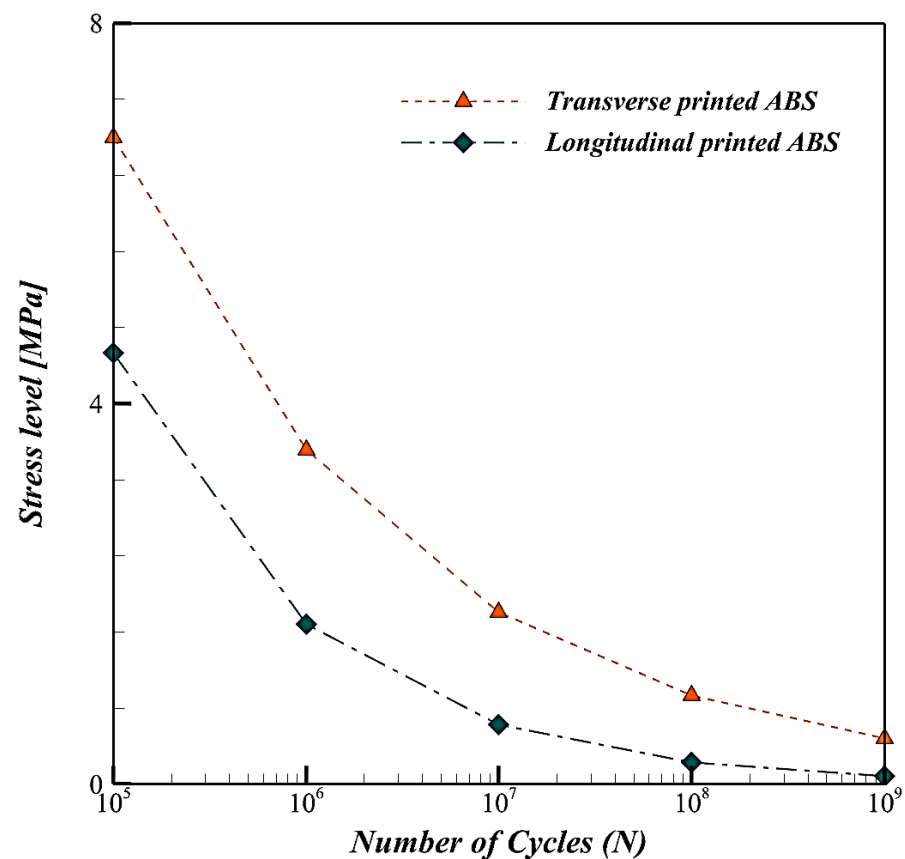


Figure 11. Fatigue lifetime of 3D-printed ABS material in two printed directions [39].

The wing produced in the experiment was fabricated using an extruder and subjected to bending loading. The S-N curve for the 3D-printed ABS material under bending loading is depicted in the ensuing figure. Notably, various printing parameters, including the printing direction, layer height, and nozzle diameter, can significantly influence the outcome. The provided chart juxtaposes the fatigue life results for two printing directions—longitudinal and transverse. Fatigue tests conducted on materials fabricated via 3D printing revealed the material's endurance in terms of cycles tolerated under specific stress amplitudes.

According to the derived S-N curve, the anticipated number of cycles for a stress amplitude of 2.22 MPa was estimated to be 4.88×10^6 when the printing direction aligned longitudinally, perpendicular to the bending direction. Conversely, with transverse printing, the projected number of cycles stood at 5.27×10^5 . These values indicate the material's ability to withstand an extensive number of cycles—virtually infinite for engineering applications. Given that the wing's printing direction was transverse, the latter figure was deemed the more pertinent estimate for cycle count.

It is worth noting that environmental factors such as temperature and humidity can influence fatigue life, assuming equivalent loading frequencies. In this study, the loading frequency was maintained at 100 Hz under ambient conditions of room temperature (25 °C).

4. Conclusions

In this study, the mechanical response and structural integrity of a tubercle leading edge under static loading conditions were comprehensively investigated. The potential of this bio-inspired design to enhance aerodynamic efficiency and ensure structural robustness, which is crucial for fluid mechanics and structure applications, was elucidated.

It was confirmed by experimental and computational analyses that a predictable linear relationship between the applied loads and induced strains existed, demonstrating the structural integrity of the tubercle leading edge. Under static loads up to 2122 g, structural integrity was maintained by the wing, with strains increasing linearly without reaching the material's yield point. The divergence observed at loads beyond 1344 g highlighted the impact of 3D printing anomalies, which, while evident, did not compromise the structural integrity.

Remarkable endurance under dynamic loading conditions was demonstrated by the tubercle leading edge, with the material enduring up to 4.88×10^6 cycles in the longitudinal orientation and 5.27×10^5 cycles in the transverse orientation. This endurance under cyclical loading conditions points to the capability of the design to enhance aerodynamic performance by maintaining lift and delaying stall, which is significant for improving the efficiency and safety of aerodynamical structures.

Significant contributions to the field were made by demonstrating the effectiveness of tubercle leading edges in improving aerodynamic efficiency and structural integrity. Important implications for the design of aerodynamical components, where efficiency and integrity are paramount, are held by these findings. The potential of tubercle leading edges to be employed in fluid mechanics applications is supported by the study's results, offering a method to enhance performance while ensuring safety. This investigation not only affirms the hypothesized benefits of the tubercle leading edge design, but also enhances our understanding of its practical applications, making a notable contribution to the field of mechanical engineering.

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References

1. Aftab, S.; Razak, N.; Rafie, A.M.; Ahmad, K. Mimicking the humpback whale: An aerodynamic perspective. *Prog. Aerosp. Sci.* **2016**, *84*, 48–69. [\[CrossRef\]](#)
2. Chen, W.; Qiao, W.; Wei, Z. Aerodynamic performance and wake development of airfoils with wavy leading edges. *Aerosp. Sci. Technol.* **2020**, *106*, 106216. [\[CrossRef\]](#)
3. Zhao, M.; Zhao, Y.; Liu, Z. Dynamic mode decomposition analysis of flow characteristics of an airfoil with leading edge protuberances. *Aerosp. Sci. Technol.* **2020**, *98*, 105684. [\[CrossRef\]](#)
4. Liu, K.; Song, B.; Xue, D.; Yang, W.; Chen, A.; Wang, Z. Numerical study of the aerodynamic effects of bio-inspired leading-edge serrations on a heaving wing at a low Reynolds number. *Aerosp. Sci. Technol.* **2022**, *124*, 107529. [\[CrossRef\]](#)
5. Liu, J.; Zhu, W.; Xiao, Z.; Sun, H.; Huang, Y.; Liu, Z. DDES with adaptive coefficient for stalled flows past a wind turbine airfoil. *Energy* **2018**, *161*, 846–858. [\[CrossRef\]](#)
6. Gopinathan, V.; Rose, J.B.R. Aerodynamics with state-of-the-art bioinspired technology: Tubercles of humpback whale. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2021**, *235*, 2359–2377. [\[CrossRef\]](#)
7. Rostamzadeh, N.; Kelso, R.M.; Dally, B.B.; Hansen, K.L. The effect of undulating leading-edge modifications on NACA 0021 airfoil characteristics. *Phys. Fluids* **2013**, *25*, 117101. [\[CrossRef\]](#)
8. Zhao, M.; Zhang, M.M.; Xu, J.Z. Flow physics behind the effects of leading-edge protuberances on the airfoil aerodynamic performance. In *Journal of Physics: Conference Series*; IOP Publishing: Bristol, UK, 2018; pp. 22–35.
9. Pérez-Torró, R.; Kim, J.W. A large-eddy simulation on a deep-stalled aerofoil with a wavy leading edge. *J. Fluid Mech.* **2017**, *813*, 23–52. [\[CrossRef\]](#)

10. Morelli, M.; Beretta, L.; Guardone, A.; Quaranta, G. Numerical Investigation of Ice Formation on a Wing with Leading-Edge Tubercles. *J. Aircr.* **2023**, *60*, 190–204. [\[CrossRef\]](#)
11. de Paula, A.A. The Airfoil Thickness Effects on Wavy Leading Edge Phenomena at Low Reynolds Number Regime. Doctoral Dissertation, Universidade de São Paulo, São Paulo, Brazil, 2016. [\[CrossRef\]](#)
12. Zhao, M.; Xu, L.; Li, X.; Zhao, Y.; Liu, Z. Dynamic stall of pitching tubercled wings in vortical wake flowfield. *Phys. Fluids* **2023**, *35*, 015122. [\[CrossRef\]](#)
13. Gonçalves, A.N.; Pereira, J.M.; Sousa, J.M. Passive control of dynamic stall in a H-Darrieus Vertical Axis Wind Turbine using blade leading-edge protuberances. *Appl. Energy* **2022**, *324*, 119700. [\[CrossRef\]](#)
14. Hryniuk, J.T.; Bohl, D.G. The effects of leading-edge tubercles on dynamic stall. *J. Fluid Mech.* **2020**, *893*, A5. [\[CrossRef\]](#)
15. Ng, B.; New, T.; Palacios, R. Effects of leading-edge tubercles on wing flutter speeds. *Bioinspiration Biomim.* **2016**, *11*, 36003. [\[CrossRef\]](#)
16. New, D.T.H.; Ng, B.F. (Eds.) *Flow Control through Bio-Inspired Leading-Edge Tubercles*; Springer International Publishing: Cham, The Netherlands, 2020; ISBN 9783030237912.
17. Butt, F.R.; Talha, T. Numerical Investigation of the Effect of Leading-Edge Tubercles on Propeller Performance. *J. Aircr.* **2019**, *56*, 1014–1028. [\[CrossRef\]](#)
18. Miklosovic, D.S.; Murray, M.M.; Howle, L.E. Experimental Evaluation of Sinusoidal Leading Edges. *J. Aircr.* **2007**, *44*, 1404–1408. [\[CrossRef\]](#)
19. Rohmawati, I.; Arai, H.; Nurjannah, I. Wavy Leading Edge (WLE) Influence on a Rectangular Wing Using an Unsteady Analysis Approach. *J. Mech. Eng. Sci. Innov.* **2023**, *3*, 43–56. [\[CrossRef\]](#)
20. Fan, M.; Sun, Z.; Dong, X.; Li, Z. Numerical and experimental investigation of bionic airfoils with leading-edge tubercles at a low-Re in considering stall delay. *Renew. Energy* **2022**, *200*, 154–168. [\[CrossRef\]](#)
21. Rohmawati, I.; Arai, H.; Nakashima, T.; Mutsuda, H.; Doi, Y. Effect of Wavy Leading Edge on Pitching Rectangular Wing. *J. Aero Aqua Bio-Mech.* **2020**, *9*, 1–7. [\[CrossRef\]](#)
22. Ke, W.; Hashem, I.; Zhang, W.; Zhu, B. Influence of leading-edge tubercles on the aerodynamic performance of a horizontal-axis wind turbine: A numerical study. *Energy* **2021**, *239*, 122186. [\[CrossRef\]](#)
23. Du, L.; Dominy, R.G.; Ingram, G. Experimental Investigation of the Performance of H-Darrieus Wind Turbines with Tubercle Leading Edge Blades. In *Turbo Expo: Power for Land, Sea, and Air*; American Society of Mechanical Engineers: New York, NY, USA, 2020; Volume 12. [\[CrossRef\]](#)
24. Joseph, J.; Sathyabhama, A. Leading edge tubercle on wind turbine blade to mitigate problems of stall, hysteresis, and laminar separation bubble. *Energy Convers. Manag.* **2022**, *255*, 115337. [\[CrossRef\]](#)
25. Sudhakar, S.; Karthikeyan, N.; Suriyanarayanan, P. Experimental Studies on the Effect of Leading-Edge Tubercles on Laminar Separation Bubble. *AIAA J.* **2019**, *57*, 5197–5207. [\[CrossRef\]](#)
26. Natarajan, K.; Sudhakar, S.; Paulpandian, S. Experimental Studies On The Effect Of Leading Edge Tubercles On Laminar Separation Bubble. In Proceedings of the 52nd Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Reston, VA, USA, 13–17 January 2014. [\[CrossRef\]](#)
27. Jabbari, H.; Djavahreshkian, M.H.; Esmaeili, A. Static roughness element effects on protuberance full-span wing at micro aerial vehicle application. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2021**, *236*, 2074–2091. [\[CrossRef\]](#)
28. Wei, Z.; Toh, J.; Ibrahim, I.; Zhang, Y. Aerodynamic characteristics and surface flow structures of moderate aspect-ratio leading-edge tubercled wings. *Eur. J. Mech.-B/Fluids* **2019**, *75*, 143–152. [\[CrossRef\]](#)
29. Tunio, I.A.; Kumar, D.; Hussain, T.; Jatoti, M. Safiullah Investigation of Variable Spanwise Waviness Wavelength Effect on Wing Aerodynamic Performance. *Fluid Dyn.* **2020**, *55*, 657–669. [\[CrossRef\]](#)
30. Fan, M.; Dong, X.; Li, Z.; Sun, Z.; Feng, L. Numerical and experimental study on flow separation control of airfoils with various leading-edge tubercles. *Ocean Eng.* **2022**, *252*, 111046. [\[CrossRef\]](#)
31. Lin, Y.-T.; Chiu, P.-H. Influence of leading-edge protuberances of fx63 airfoil for horizontal-axis wind turbine on power performance. *Sustain. Energy Technol. Assess.* **2020**, *38*, 100675. [\[CrossRef\]](#)
32. Shi, W.; Rosli, R.; Atlar, M.; Norman, R.; Wang, D.; Yang, W. Hydrodynamic performance evaluation of a tidal turbine with leading-edge tubercles. *Ocean Eng.* **2016**, *117*, 246–253. [\[CrossRef\]](#)
33. Fan, M.; Sun, Z.; Yu, R.; Dong, X.; Li, Z.; Bai, Y. Effect of leading-edge tubercles on the hydrodynamic characteristics and wake development of tidal turbines. *J. Fluids Struct.* **2023**, *119*, 103873. [\[CrossRef\]](#)
34. Kant, R.; Bhattacharyya, A. A bio-inspired twin-protuberance hydrofoil design. *Ocean Eng.* **2020**, *218*, 108209. [\[CrossRef\]](#)
35. McGhee, R.J.; Beasley, W.D.; Somers, D.M. *Low-Speed Aerodynamics Characteristics of a 17-Percent-Thick Airfoil Section Designed for General Aviation Applications*; [for sale by the National Technical Information Service], Washington D.C.; National Aeronautics and Space Administration: Washington, DC, USA; Springfield, VA, USA, 1973.
36. Johari, H.; Henoch, C.; Custodio, D.; Levshin, A. Effects of Leading-Edge Protuberances on Airfoil Performance. *AIAA J.* **2007**, *45*, 2634–2642. [\[CrossRef\]](#)
37. Guerreiro, J.L.E.; Sousa, J.M.M. Low-Reynolds-Number Effects in Passive Stall Control Using Sinusoidal Leading Edges. *AIAA J.* **2012**, *50*, 461–469. [\[CrossRef\]](#)

38. Tezel, T.; Kovan, V. Determination of optimum production parameters for 3D printers based on nozzle diameter. *Rapid Prototyp. J.* **2021**, *28*, 185–194. [[CrossRef](#)]
39. Azadi, M.; Dadashi, A.; Sadegh, M.; Parast, A.; Dezianian, S. A Comparative Study for High-Cycle Bending Fatigue Lifetime and Fracture Behavior of Extruded and Additive-Manufactured 3D-Printed Acrylonitrile Butadiene Styrene Polymers. *Int. J. Addit.-Manuf. Struct.* **2022**, *12*, 1–10. [[CrossRef](#)]

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