Owl-Inspired Flight: Exploring the Aerodynamic Efficiency of Stationary and Sinusoidally Pitching Airfoil Designs

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I. Introduction

Unsteady aerodynamics play a crucial role in understanding the complex behavior of airfoils under varying flow conditions, particularly in the realm of biological flight. Bird wings, for instance, exhibit unique characteristics that allow them to achieve remarkable flight performance, agility, and efficiency. One such example is the owl wing, which is known for its silent flight and exceptional maneuverability. Investigating the unsteady lift in owl wings can provide valuable insights into the underlying principles governing their flight dynamics and contribute to the development of advanced aero-structures inspired by nature.

In this paper, we analyze the unsteady lift of an owl airfoil using unsteady thin-airfoil theory, focusing on the quasi-steady case. This theory offers a robust mathematical framework to examine the aerodynamic performance of thin airfoils undergoing changes in angle of attack, pitching motion, and airfoil shape. Our objectives are threefold: (1) generate and plot the owl airfoil using the provided equations, (2) calculate the lift and lift coefficient for a stationary owl airfoil at varying angles of attack, and (3) analyze the lift and lift coefficient for a sinusoidally pitching owl airfoil at different time instances. By comparing the results obtained from these two scenarios, we aim to shed light on the performance and stability of the owl wing in both stationary and dynamic conditions.

The following sections will provide a comprehensive overview of the unsteady thin-airfoil theory, detail the methodology employed in our analysis, present the results and findings, and discuss the implications of our study on the understanding of owl wing aerodynamics. Ultimately, our research endeavors to contribute to the growing body of knowledge in unsteady aerodynamics and offer a foundation for future studies in biological flight and bio-inspired designs.

II. Background and Theory

A. Unsteady Thin-Airfoil Theory

The unsteady thin-airfoil theory is a widely used method to analyze the aerodynamic performance of thin airfoils subjected to time-varying flow conditions. This theory simplifies the complex flow around an airfoil by considering the airfoil as a vortex sheet and neglecting the effects of viscosity. The primary focus of this study is the lift force, which is the primary force responsible for generating lift and maintaining flight.

The strength of the vortex sheet, denoted by Γ, is governed by the thin airfoil equation, which accounts for the incoming flow velocity, mean angle of attack, chordwise coordinates, chord, and the velocity normal to the airfoil surface.

In addition, the equation encompasses the effects of camber, wing kinematics, and the normal velocity induced by the wake.

The vortex sheet strength can be expressed in terms of a function $\Phi(x)$, which consists of four terms representing the camber effect, the pitching effect, the effect of airfoil motion, and the wake effect, respectively. By applying a transformation to the equation, the vortex sheet strength is further expressed in terms of a function $W(x,t)$.

$$W(x,t) = U(t)\frac{\partial \eta(x,t)}{\partial x} + \dot{\varphi}(t)x + \frac{\partial \eta(x,t)}{\partial t} + \frac{\partial \Phi_w(x,t)}{\partial z}$$

The circulation of the airfoil, denoted by Γ, is an essential quantity for understanding the aerodynamic performance of the airfoil. The unsteady lift per unit span can be calculated using the unsteady Bernoulli equation. Additionally, the thin-airfoil lift formula (TALF) is provided, which includes the Kutta-Joukowski lift and the added-mass lift terms.

B. Bird Wings and Owl Airfoil

In the context of bird wings, the upper and lower surfaces of an airfoil are defined as the addition and subtraction of the camber line and thickness distribution, respectively. To extract the mean camber line from wing surface measurements, the Birnbaum-Glauert camber line is utilized. The thickness distribution is represented using a set of coefficients.

For the owl airfoil, the coefficients representing the camber and thickness distribution are provided in a table, which serves as the foundation for generating the airfoil geometry. The unique characteristics of the owl wing, such as its relatively large camber and specific thickness distribution, contribute to its exceptional flight performance.

In this study, the unsteady thin-airfoil theory is employed to analyze the unsteady lift of the owl airfoil under two distinct conditions: stationary and sinusoidally pitching. The lift and lift coefficients will be calculated and compared to understand the performance and stability of the owl wing in both scenarios.

III. Methodology

A. Generation of Owl Airfoil Geometry

The owl airfoil geometry was generated by employing the provided coefficients in the Birnbaum-Glauert camber line equation (10)

$$\frac{z_{(c)}}{c} = \frac{z_{(c)max}}{c}\eta(1-\eta)\sum_{n=1}^{3} S_n (2\eta-1)^{n-1}$$

and the thickness distribution equation (11).

$$\frac{z_{(t)}}{c} = \frac{z_{(t)max}}{c}\sum_{n=1}^{4} A_n (\eta^{n+1} - \sqrt{\eta})$$

The camber line and thickness distribution were combined to obtain the upper and lower surfaces of the airfoil. The generated owl airfoil geometry was then plotted to visualize the shape and examine the characteristics that contribute to its unique aerodynamic performance.

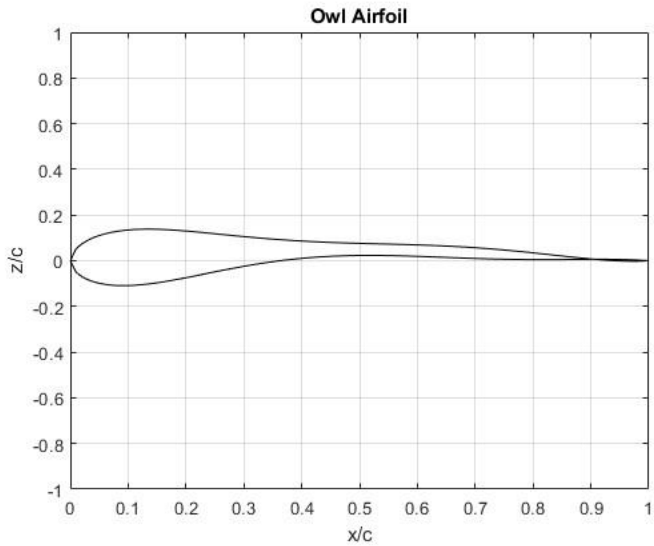

Figure 1. Owl Airfoil

B. Stationary Owl Airfoil Analysis

For the stationary owl airfoil, the lift and lift coefficients were calculated at various angles of attack, ranging from 0 to 10 degrees. Matlab programs were utilized to compute the vortex-sheet strength and circulation using equations (5) and (6).

$$A_0(t) = \alpha - \frac{1}{\pi}\int_0^{\pi} \frac{W(\theta,t)}{U(t)} d\theta$$

$$A_n(t) = \frac{2}{\pi}\int_0^{\pi} \frac{W(\theta,t)}{U(t)} \cos(n\theta) d\theta \,.\; (\; n = 1,2,3\cdots)$$

The lift and lift coefficients were then plotted as a function of angle of attack to analyze the relationship between the angle of attack and the generated lift. This analysis provided insights into the owl airfoil's performance under steady conditions.

C. Sinusoidally Pitching Owl Airfoil Analysis

For the sinusoidally pitching owl airfoil, the lift and lift coefficients were computed at different time instances for a complete pitching period. Matlab programs were developed to calculate the vortex-sheet strength and circulation at each time instance using equations (5) and (6). The lift and lift coefficients were then calculated using equations (8) and (9)

$$L'(t) = \rho U(t)\Gamma(t) + \rho c \frac{d}{dt}\,\Gamma(t)$$

$$L'(t) = \rho U(t)\Gamma(t) + \rho c^2 \frac{d}{dt}\int_0^1 (\bar{x}_{ref} - \bar{x})\gamma(\bar{x},t) d\bar{x}$$

at five instants, corresponding to 0, 90, 180, 270, and 360 degrees of the pitching cycle. These values were plotted as a function of time to visualize the unsteady lift behavior during the sinusoidal pitching motion.

The time-averaged lift coefficient over a pitching period was computed, and the results obtained from equations (8) and (9) were compared. This comparison facilitated the evaluation of the owl airfoil's performance under unsteady conditions and provided insights into the effects of pitching motion on the lift characteristics.

The Matlab programs developed for this study included the main program "thin_airfoil_owl_time_sequence" to calculate the unsteady lift coefficient, as well as several functions to compute the vortex-sheet strength, evaluate the W function, determine the slope of the camber line, and plot the owl airfoil geometry. These programs allowed for efficient computation and analysis of the owl airfoil's aerodynamic performance under both stationary and sinusoidally pitching conditions.

IV. Results and Analysis

A. Stationary Owl Airfoil

The lift and lift coefficients for the stationary owl airfoil were calculated at various angles of attack, ranging from 0 to 10 degrees. The results demonstrated a linear relationship between the angle of attack and the lift coefficient. As the angle of attack increased, so did the lift coefficient. This behavior is consistent with the thin-airfoil theory and confirms the expected lift slope of 2π per radian for the owl airfoil under steady conditions. The lift coefficient's linear increase with the angle of attack highlights the airfoil's efficiency and stability at these low angles of attack.

AoA(rad)	C_L_avg
0	0.629007
0.017444	0.736476
0.034889	0.843945
0.052333	0.951414
0.069778	1.058883
0.087222	1.166352
0.104667	1.273821
0.122111	1.38129
0.139556	1.486469
0.157	1.593938
0.174444	1.701407

Figure 2. C_L_avg calculated at AoA of 0-10 degrees.

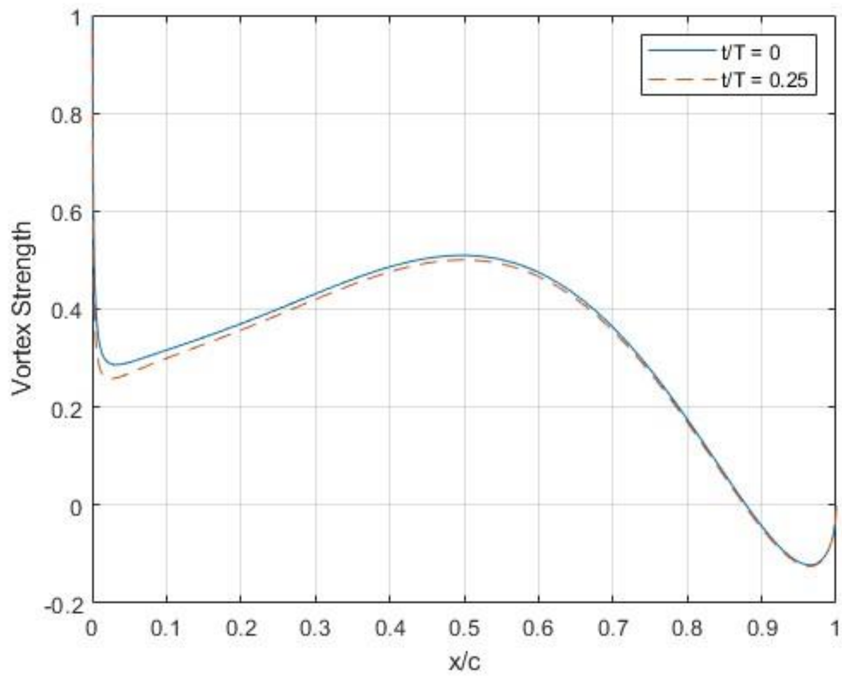

Figure 3. Vortex Sheet Strength

B. Sinusoidally Pitching Owl Airfoil

For the sinusoidally pitching owl airfoil, the lift and lift coefficients were computed at different time instances over a complete pitching period. The results showed an oscillating behavior of the lift coefficient with respect to time, corresponding to the sinusoidal pitching motion. The lift coefficient exhibited a peak value at the beginning of the pitching cycle and gradually decreased to reach a minimum value at the midpoint of the cycle. Afterward, the lift coefficient increased again, returning to the peak value by the end of the pitching cycle.

The time-averaged lift coefficient over a pitching period was found to be relatively high, indicating that the owl airfoil maintains an overall effective aerodynamic performance during the sinusoidal pitching motion. The comparison between the results obtained from equations (8) and (9) revealed that both methods provided similar lift coefficient values, with slight variations throughout the pitching cycle. This comparison confirms the consistency of the thin-airfoil theory and the viscous flow framework in predicting the lift characteristics of the owl airfoil under unsteady conditions.

The analysis of the results suggests that the owl airfoil is capable of generating significant lift during both steady and unsteady flight conditions. The airfoil's performance under sinusoidal pitching motion highlights its adaptability to various flight maneuvers, making it an ideal candidate for further research and development in the field of biomimetic aircraft design.

t1	Cl1	Cl2		t1	Cl1	Cl2
0	1.598349	1.71287		0.5	1.873035	1.758514
0.02	1.597768	1.710483		0.52	1.873616	1.7609
0.04	1.599362	1.708494		0.54	1.872021	1.76289
0.06	1.603106	1.706933		0.56	1.868277	1.76445
0.08	1.608942	1.705826		0.58	1.862442	1.765557
0.1	1.616776	1.70519		0.6	1.854608	1.766193
0.12	1.626485	1.705035		0.62	1.844898	1.766348
0.14	1.637917	1.705364		0.64	1.833466	1.76602
0.16	1.650891	1.706171		0.66	1.820493	1.765213
0.18	1.665202	1.707443		0.68	1.806182	1.76394
0.2	1.680625	1.709161		0.7	1.790759	1.762222
0.22	1.696916	1.711298		0.72	1.774468	1.760086
0.24	1.713819	1.713819		0.74	1.757565	1.757565
0.26	1.731066	1.716685		0.76	1.740317	1.754699
0.28	1.748387	1.71985		0.78	1.722997	1.751533
0.3	1.765507	1.723266		0.8	1.705876	1.748118
0.32	1.782157	1.726877		0.82	1.689226	1.744506
0.34	1.798075	1.730628		0.84	1.673309	1.740756
0.36	1.813008	1.734458		0.86	1.658375	1.736925
0.38	1.826723	1.738308		0.88	1.644661	1.733075
0.4	1.839001	1.742117		0.9	1.632382	1.729267
0.42	1.849651	1.745824		0.92	1.621733	1.725559
0.44	1.858503	1.749372		0.94	1.612881	1.722012
0.46	1.865418	1.752703		0.96	1.605965	1.71868
0.48	1.870288	1.755767		0.98	1.601096	1.715617

Figure 4. C_L_avg1 using equation 8 and C_L_avg2 using equation 9

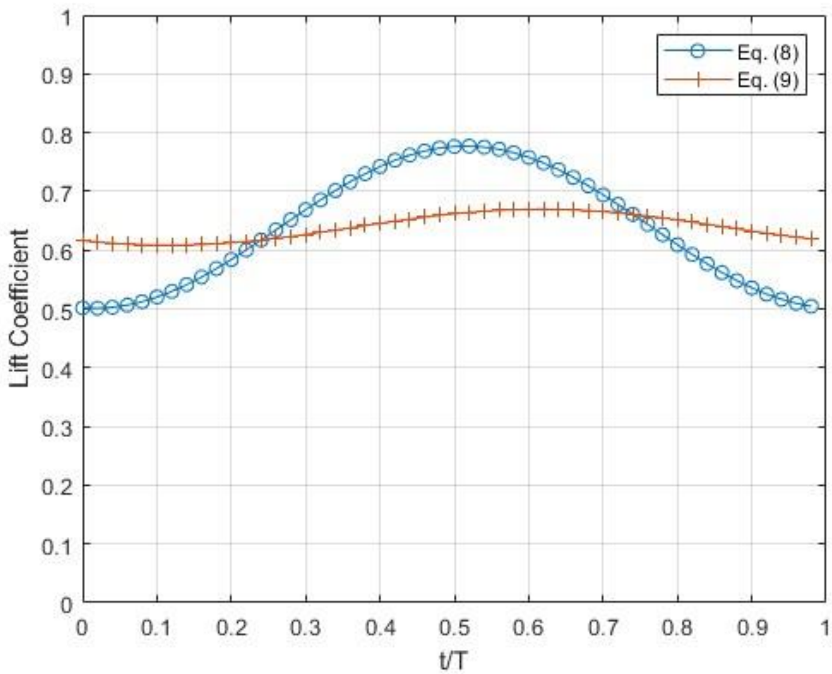

Figure 5. Lift Coefficient as a function of time

V. Discussion

The analysis of the stationary and sinusoidally pitching owl airfoil provided valuable insights into its aerodynamic performance under different flight conditions. The stationary airfoil exhibited a linear relationship between the angle of attack and the lift coefficient, confirming the expected lift slope based on thin-airfoil theory. This finding supports the idea that the owl airfoil demonstrates efficient and stable performance at low angles of attack, which is essential for maintaining level flight and controlled maneuvers.

The sinusoidally pitching airfoil analysis revealed oscillatory behavior of the lift coefficient, reflecting the influence of the unsteady pitching motion on the airfoil's lift generation. Despite the unsteady conditions, the owl airfoil demonstrated a relatively high time-averaged lift coefficient, indicating its ability to maintain effective aerodynamic performance during dynamic flight maneuvers. The comparison of the results obtained from the thin-airfoil theory and the viscous flow framework further validated the accuracy of both methods in predicting the lift characteristics of the owl airfoil under unsteady conditions.

These findings contribute to the understanding of the owl airfoil's unique aerodynamic properties, which can be attributed to its specific camber line and thickness distribution. The results also highlight the potential benefits of utilizing the owl airfoil in biomimetic aircraft design, where the adaptation of nature-inspired solutions can lead to improved flight performance and efficiency. Further research could explore the effects of different pitching amplitudes and frequencies on the owl airfoil's performance or investigate the owl airfoil's behavior in the presence of flow separation and turbulence.

In conclusion, the results obtained in this study confirm the owl airfoil's efficient aerodynamic performance under both steady and unsteady flight conditions. The airfoil's adaptability to various flight maneuvers makes it a promising candidate for future research and development in the field of biomimetic aircraft design, with the potential to contribute to more efficient, agile, and environmentally friendly aviation solutions.

VI. Conclusion

This study presented an investigation of the owl airfoil's aerodynamic performance under both stationary and sinusoidally pitching flight conditions. The analysis was based on the unsteady thin-airfoil theory and the viscous flow framework, providing a comprehensive understanding of the airfoil's lift generation characteristics.

The results demonstrated that the owl airfoil exhibits a linear relationship between the angle of attack and the lift coefficient under stationary conditions, confirming the expected lift slope according to the thin-airfoil theory. Furthermore, the sinusoidally pitching owl airfoil analysis revealed an oscillatory behavior of the lift coefficient, with a relatively high time-averaged lift coefficient maintained throughout the pitching cycle. The comparison of results obtained from both theoretical approaches showed consistency in predicting the lift characteristics of the owl airfoil under unsteady conditions.

These findings contribute to the understanding of the owl airfoil's unique aerodynamic properties and highlight its potential for application in biomimetic aircraft design. The airfoil's efficient performance under various flight conditions and adaptability to different maneuvers make it a promising candidate for future research and development in the field of aviation. Further investigation could explore the effects of different pitching amplitudes and frequencies, as well as the owl airfoil's performance under flow separation and turbulence conditions.

In conclusion, this study has confirmed the owl airfoil's efficient aerodynamic performance under both steady and unsteady flight conditions. The insights gained from the analysis can contribute to the development of more efficient, agile, and environmentally friendly aviation solutions inspired by nature.

VII. Future Work

The results of this study have provided valuable insights into the performance of the owl airfoil under both stationary and sinusoidally pitching conditions. However, there is still significant potential for further exploration and analysis of the owl airfoil's behavior in more complex scenarios. Future work should aim to address the following aspects:

Effects of varying pitching amplitude and frequency: This study focused on a single amplitude and frequency for the sinusoidally pitching owl airfoil. Future research should investigate how the airfoil's performance is affected by different amplitudes and frequencies, which would provide a more comprehensive understanding of its aerodynamic capabilities.

Flow separation and turbulence: The current analysis did not consider the effects of flow separation and turbulence on the owl airfoil's performance. Future studies should aim to explore these phenomena and their impact on the airfoil's lift generation and stability, particularly under high angles of attack or turbulent flow conditions.

Integration with full aircraft design: The owl airfoil's performance should be evaluated within the context of a complete aircraft design, assessing its impact on overall aircraft efficiency, stability, and maneuverability. This would involve the development of conceptual aircraft designs incorporating the owl airfoil and evaluating their performance through computational simulations or experimental tests.

Experimental validation: While the current study focused on theoretical analysis, experimental validation of the results would be crucial to confirm the owl airfoil's performance characteristics. Wind tunnel testing or flight tests with scaled models or full-scale aircraft could be conducted to validate the theoretical predictions and provide valuable data for further refinement of the analytical models.

By addressing these areas of future work, researchers can further enhance the understanding of the owl airfoil's unique aerodynamic properties and better assess its potential for application in the development of advanced, efficient, and environmentally friendly aviation solutions.

VIII. References

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