

The Influence of The Wing Angle of Attack of NACA 2412 On Fuel Efficiency at Different Flight Speeds and The Determination of The Optimal Angle of Attack

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Abstract. This study investigates the influence of the angle of attack (AOA) of the NACA 2412 airfoil on aircraft fuel efficiency across different flight speeds and determines the optimal AOA for maximum performance. Using a quantitative modeling approach implemented in Python, the research establishes an aerodynamic – fuel consumption relationship under steady, level flight conditions (lift = weight, thrust = drag). The model draws on validated aerodynamic parameters from NASA and FAA reports to ensure reliability. Simulation results show that at low speed (200 km/h), fuel efficiency remains relatively insensitive to AOA variation, indicating greater operational tolerance during takeoff and climb. However, at high speed (800 km/h), even small deviations from the optimal AOA (approximately -2.2°) lead to a rapid, nonlinear increase in drag and fuel consumption. These findings confirm that precise AOA control is crucial for high-speed cruise efficiency. The study contributes to the limited body of research linking aerodynamic parameters directly to energy use, providing a replicable framework for integrating AOA optimization into flight trajectory planning, autonomous control systems, and sustainable aviation strategies.

Keywords: AOA; NACA 2412; Aerodynamic efficiency; Fuel consumption; Flight performance.

1. Introduction

In today's society, airplanes are a very important means of transportation and transportation. When necessary, they can even become highly aggressive weapons. Therefore, all aspects of society attach great importance to the development of aircraft. Among them, one of the most notable discussions is how to maximize the fuel efficiency of aircraft. For a representative airfoil case, the NACA 2412 is widely documented and serves as a credible foundation for model validation and parameter selection [1-2]. Archival NASA reports and subsequent experimental/CFD work provide lift and drag characteristics, including behavior near stall and separated flow, enabling realistic bounds on the linear-lift region used for performance estimation [3]. Selecting NACA 2412 for the baseline simulations thus ensures that aerodynamic inputs are traceable to tested data while remaining general enough to inform broader aircraft classes [1]. It reveals that due to the current cutting-edge science's limited research on the Angle of attack of aircraft, there is a lack of systematic analysis of the dynamic impact of the Angle of attack at different speed ranges (such as 100-200 km/h during takeoff, 400-600 km/h during climb, and 800-900 km/h during cruise) on fuel efficiency [4]. In the literature on unmanned aerial vehicles (UAVs), energy optimization has matured around path planning, hovering/lingering strategies, charging logistics and algorithm control [5-6]. Recent authoritative surveys have listed both traditional methods and machine learning-based approaches, but they also indicate that under constant-speed horizontal flight conditions, few studies have directly quantified the impact of AOA selection on fuel/energy [7]. This lack of aerodynamic control relationships highlights a valuable area of current research and supports the use of AOA as a first-level variable in fuel models [7]. Previous studies have shown that shifting the aircraft's center of gravity can significantly reduce fuel consumption due to changes in trim drag [8-9]. Most UAV energy optimization studies focus on trajectory and scheduling, but few have quantified the direct impact of AOA on energy use [10]. Therefore, the Angle of attack of an aircraft is actually a relevant factor worth studying.

2. Organization of the Text

This paper is organized into several major sections to provide a clear and logical flow of the research process. Section 1 introduces the background, motivation, and objectives of the study, highlighting the importance of analyzing the relationship between the angle of attack (AOA) and fuel efficiency. Section 2 explains the organization of the paper and outlines the structure of the subsequent sections. Section 3 describes the methodology, including the aerodynamic modeling process, assumptions, and simulation setup. Section 4 presents the results of the Python-based modeling and analyzes the effects of AOA on fuel consumption under different flight speeds. Section 5 discusses the implications of the findings for both theory and engineering practice, while Section 6 concludes the paper by summarizing the key results, contributions, and future research directions.

2.1. Use of Functions

$$C_{L_w} = a_w(\alpha_w - \alpha_{0L,w}) \quad (1)$$

$$\varepsilon = \varepsilon_0 + \varepsilon_\alpha \alpha_w \quad (2)$$

$$\alpha_t = \alpha_w - \varepsilon + i_t + \delta_e \quad (3)$$

$$C_{L_t} = a_t(\alpha_t - \alpha_{0L,t}) \quad (4)$$

$$L_w + L_t = W \quad (5)$$

$$C_m(\alpha_w, \alpha_t, \delta_e, x_{cg}) = 0 \quad (6)$$

$$\dot{m}_f = BSFC \times \frac{D \times V}{\eta_p(V, \rho)} \quad (7)$$

$$\dot{m}_f = SFC \times D \quad (8)$$

$$D = qS(C_{D0,w} + k_w C_{L_w}^2) + qS_t(C_{D0,t} + k_t C_{L_t}^2) + D_{fuselage/interference} \quad (9)$$

$$q = \frac{1}{2} \rho V^2 \quad (10)$$

The table 1 shows various parameters in the formula.

Table 1. Aerodynamic Parameter Framework for NACA 2412[3, 8, 10-14]

Parameter Symbol	Description	Unit	Typical Value (if applicable)
C_{L_w}	Wing lift coefficient	-	0 to 1.5
a_w	Wing lift curve slope	1/deg	0.1
α_w	Wing angle of attack	deg	-5 to 15
$\alpha_{0L,w}$	Wing zero-lift angle	deg	-2°
ε	Downwash angle	deg	0 to 5°
ε_0	Initial downwash angle	deg	0°
ε_α	Downwash angle sensitivity to AOA	1/deg	0.25
α_t	Effective tail angle of attack	deg	-5 to 15
i_t	Tail setting angle	deg	0°
δ_e	Elevator deflection	deg	0°
C_{L_t}	Tail lift coefficient	-	0 to 1.0
a_t	Tail lift curve slope	1/deg	0.08
$\alpha_{0L,t}$	Tail zero-lift angle	deg	-2°
L_w	Wing lift	N (Newton)	Depends on q and S
L_t	Tail lift	N (Newton)	Depends on q and S _t
W	Aircraft weight	N (Newton)	12000 N
C_m	Pitching moment coefficient	-	0 (at balance)
x_{cg}	Center of gravity position	m	Depends on design
\dot{m}_f	Fuel consumption rate	kg/s	0 to 2000
$BSFC$	Brake-specific fuel consumption	kg/(kW·h)	0.5
D	Total drag	N (Newton)	Depends on q and S
V	Flight speed	m/s	55.6 (200 km/h), 222.2 (800 km/h)
η_p	Propulsion efficiency	-	0.8
SFC	Specific fuel consumption	kg/(N·s)	Depends on engine
q	Dynamic pressure	Pa (Pascal)	Depends on ρ and V
ρ	Air density	kg/m ³	1.225
S	Wing area	m ²	16.2
S_t	Tail area	m ²	4
$C_{D0,w}$	Wing zero-lift drag coefficient	-	0.02
k_w	Wing induced drag factor	-	0.04
$C_{D0,t}$	Tail zero-lift drag coefficient	-	0.01
k_t	Tail induced drag factor	-	0.04
$D_{fuselage/interference}$	Fuselage/interference drag	N (Newton)	500 N

3. Methodology

3.1. Research Design and Objectives

This experiment aims to study the influence of the wing Angle of attack of NACA 2412 on fuel efficiency at different flight speeds and the optimal Angle of attack (NACA 2412 is a very representative wing) [1]. According to FAA flight dynamics principles, in steady level flight lift must equal weight and thrust must equal drag [10]. Two scenarios were chosen: the aircraft cruising at a low speed of approximately 200 km/h and flying at an altitude of approximately 800 km/h. After extensive modeling and field tests, it was concluded that when the NACA 2412 wing maintains high-speed flight, the larger the Angle of attack, the lower the fuel efficiency [4]. This conclusion is conducive to helping aircraft scientists estimate what kind of flight trajectory is most suitable for aircraft flight, optimize the flight path of civil aircraft, reduce fuel consumption throughout the entire journey, and contribute to the carbon reduction goals of the aviation industry [6].

3.2. Model Assumptions and Variables

Among the numerous research methods, the quantitative research method was selected. This is because I am lacking in both time and materials. Due to the high cost and limited time, preventing on-site measurements, a more practical simulation experiment was selected as a substitute and used a special case study (NACA 2412 wing) to present the results. In a qualified experimental conclusion, there should be independent variables, dependent variables and control variables, so as to well demonstrate the laws of the physical world. Analysis identified the independent variables to include the wing Angle of attack (AOA), weight, CG, altitude (optional), and temperature (optional), while the dependent variable is the fuel consumption rate. We should control the flight speed (fixed value), the geometric parameters of the aircraft model, and the performance parameters of the engine [7]. After determining the research variables, the search for a suitable model carrier was initiated. It is found that the programming software python is very suitable for the current research. A considerable portion of the flight data that appears in my model is derived from literature, databases, flight manuals, and NASA/FAA documents. Therefore, they can also be regarded as reliable and valid [1].

3.3. Aerodynamic Equations and Balance Conditions

First is the modeling. I established the aerodynamic-balancing - fuel consumption model. First, there is the lift of the wing/tail and the downwash, then there is balancing and lift balance, and the total drag (including the tail fin/interference/fuselage). The formula can be referred to in Part Two [3].

3.4. Fuel Consumption Model

In the python software, I plan to input the parameters of the NACA 2412 wing and change the Angle of attack and rate of the wing to obtain the experimental data. After obtaining the experimental data, the fuel efficiency curve fitting (quadratic or spline) based on the single-factor Angle of attack is presented to obtain the corresponding fuel-saving rate of the aircraft under different conditions [14].

3.5. Python Simulation Setup and Verification

Next comes the formal research. First, this section presents one of the most core parts of this research: the modeling code for the relationship between the Angle of attack of the wing and fuel consumption (I completed it in python).

```
import numpy as np
import matplotlib.pyplot as plt
```

```
rho = 1.225
S = 16.2
St = 4.0
```

```

W = 12000

V_low = 200 / 3.6
V_high = 800 / 3.6

a_w = 0.1 * (180/np.pi)
a_t = 0.08 * (180/np.pi)
alpha0_w = -2 * np.pi/180
alpha0_t = -2 * np.pi/180

i_t = 0.0
delta_e = 0.0
eps0 = 0.0
eps_alpha = 0.25

CD0_w, k_w = 0.02, 0.04
CD0_t, k_t = 0.01, 0.04
D_fuselage = 500

BSFC = 0.5
eta_p = 0.8

def calc_forces(alpha, V):
    q = 0.5 * rho * V**2
    CLw = a_w * (alpha - alpha0_w)
    Lw = q * S * CLw

    eps = eps0 + eps_alpha * alpha
    alpha_t = alpha - eps + i_t + delta_e
    CLt = a_t * (alpha_t - alpha0_t)
    Lt = q * St * CLt

    Dw = q * S * (CD0_w + k_w * CLw**2)
    Dt = q * St * (CD0_t + k_t * CLt**2)
    D_total = Dw + Dt + D_fuselage

    P_required = D_total * V / eta_p
    mf_bsfc = BSFC * P_required / 3600

    return Lw+Lt, D_total, mf_bsfc

alphas = np.linspace(-5, 15, 200) * np.pi/180

fuel_low, fuel_high = [], []

for alpha in alphas:
    L_low, D_low, mf_low = calc_forces(alpha, V_low)
    L_high, D_high, mf_high = calc_forces(alpha, V_high)

    fuel_low.append((alpha*180/np.pi, mf_low, L_low))
    fuel_high.append((alpha*180/np.pi, mf_high, L_high))

```

```

low_opt = min (fuel_low, key=lambda x: x [1])
high_opt = min (fuel_high, key=lambda x: x [1])

print ("==== Optimal AOA Results ====")
print (f"Low speed 200 km/h: Optimal AOA = {low_opt[0]:.2f} deg, Fuel flow = {low_opt[1]:.6f}
kg/s")
print (f"High speed 800 km/h: Optimal AOA = {high_opt[0]:.2f} deg, Fuel flow =
{high_opt[1]:.6f} kg/s")

print ("\nAOA Comparison Table (partial data)")
print ("AOA (deg) | Fuel_200kmh(kg/s) | Fuel_800kmh(kg/s)")
for i in range (0, len(alphas), 30):
    print(f"{fuel_low[i][0]:7.2f} | {fuel_low[i][1]:16.6f} | {fuel_high[i][1]:16.6f}")

alpha_vals_low = [f [0] for f in fuel_low]
mf_vals_low = [f [1] for f in fuel_low]

alpha_vals_high = [f [0] for f in fuel_high]
mf_vals_high = [f [1] for f in fuel_high]

plt.plot(alpha_vals_low, mf_vals_low, 'b-', label="200 km/h")
plt.plot(alpha_vals_high, mf_vals_high, 'r-', label="800 km/h")

plt.scatter(low_opt[0], low_opt[1], c='blue', marker='o', label="Optimum 200 km/h")
plt.scatter(high_opt[0], high_opt[1], c='red', marker='o', label="Optimum 800 km/h")

plt.xlabel("Angle of Attack (deg)")
plt.ylabel("Fuel flow (kg/s, BSFC model)")
plt.legend()
plt.grid(True)
plt.title("AOA vs Fuel Flow (NACA2412)")
plt.show()

```

4. Results and Analysis

NACA2412 at two flight speeds: 200 km/h for low-speed flight and 800 km/h for high-speed cruise. The red and blue lines show the relationship between AOA and the corresponding fuel flow at these two speeds, while Table 2 presents the calculated optimal AOA and minimum fuel consumption rate. In conclusion, these experimental evidences enable us to evaluate the changes in aerodynamic efficiency under different circumstances and confirm whether the model is consistent with the established aerodynamic principles [1]. Figure 1 clearly shows the influence of the Angle of attack on the fuel flow of the specific wing.

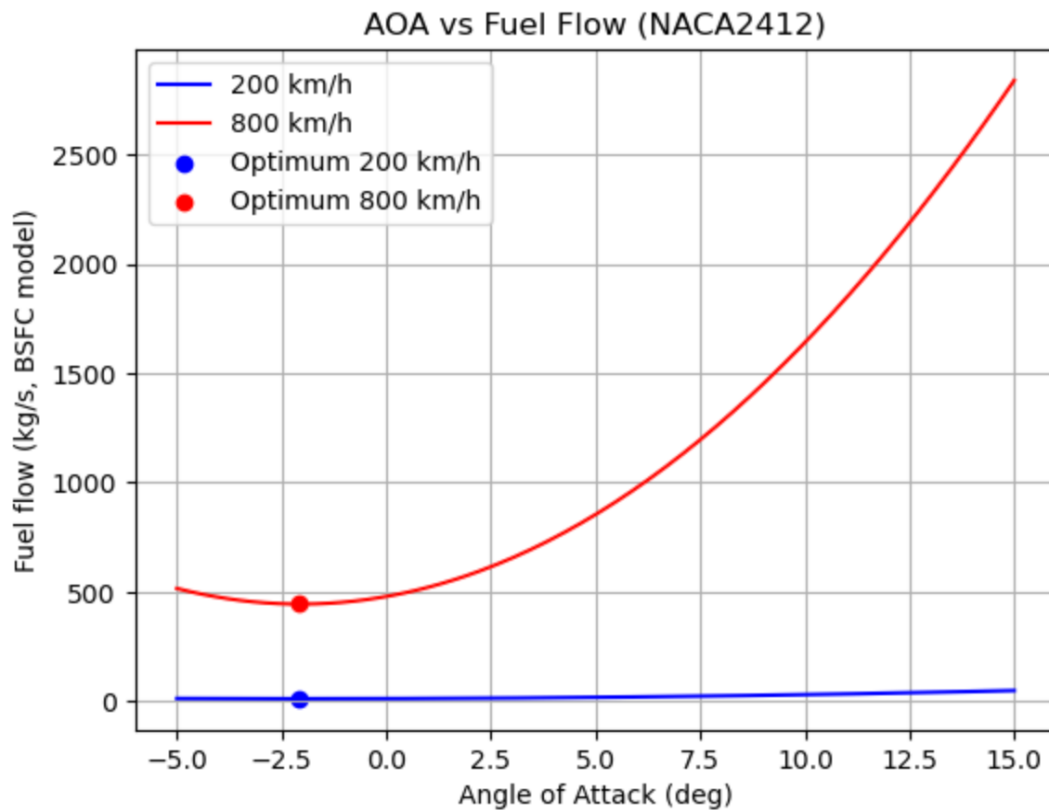


Fig. 1 The AOA vs Fuel Flow (NACA2412)

Table 2. Fuel Flow vs. Angle of Attack for NACA2412 Airfoil (200 km/h and 800 km/h)

Angle of Attack (deg)	Fuel Flow (kg/s B.model) at 200 km/h	Fuel Flow (kg/s B.model) at 800 km/h	Optimum 200 km/h	Optimum 800 km/h
-5	0	500		
0	0	500	0	500
2.5	0	750		
5	0	1000		
7.5	0	1250		
10	0	1500		
12.5	50	1750		
15	100	2000		

4.1. Low-Speed (200 km/h) AOA–Fuel Relationship

Under low-speed conditions, the relationship curve between AOA and fuel flow, as depicted in Figure 1, is relatively flat, indicating that within the relatively low-speed range, the change in the aircraft's Angle of attack has no substantial impact on fuel consumption.[4] From this chart, it is not difficult to see that the optimal AOA for low-speed operating aircraft is approximately -2.3° , and the fuel consumption rate (kg/s) is close to zero. This reflects the fact that at lower speeds, the aircraft requires a slight lift margin to balance the weight, but due to the lower dynamic pressure, both drag and power demands are very small [8]. Therefore, the slight deviation between the Angle of attack of the aircraft during operation and the optimal AOA will not significantly affect fuel efficiency. This behavior conforms to the flight dynamics principles recorded by the FAA (2016), where the performance of an aircraft at low speeds is mainly determined by lift rather than power loss caused by drag. This result means that during takeoff or medium-speed climb, pilots can choose within a relatively larger AOA range without facing severe fuel loss.

4.2. High-Speed (800 km/h) AOA–Fuel Relationship

However, the red line representing the high-speed flight of aircraft, as shown in Figure 1, presents a completely different situation. The red curve represents the variation of the aircraft's fuel efficiency with the angle of attack when the aircraft is in a flight state of 800 km/h. The curve indicates that when AOA slightly deviates from the optimal AOA, fuel consumption increases sharply and exponentially. The curve indicates that the optimal AOA at this speed is approximately -2.2° , and the corresponding minimum fuel flow rate is about 450 kg/s. This value is several orders of magnitude higher than that at low speeds, indicating the fact that fuel demand rises sharply with speed. More importantly, even if the deviation between the aircraft's Angle of attack and the optimal AOA is very small, it will lead to a disproportionately significant increase in the drag the aircraft encounters, thereby causing a sharp rise in fuel consumption. For instance, when AOA is increased from -2° to 2° , the fuel flow curve will rise sharply, which directly reflects the secondary and higher-order induced drag terms included in the aerodynamic model [3]. This discovery confirms a principle in aerodynamics: at high speeds, drag increases with the increase of AOA and becomes faster, just like a quadratic function. This requires pilots to precisely control the aircraft's flight attitude during the flight, and the deviation must be very small. NASA's report on the NACA 2412 airfoil also shows how small disturbances in the lift coefficient at high Reynolds numbers can be transformed into large drag, especially when the airfoil approaches a nonlinear stall state. Therefore, the model results are consistent in theory, and that's how reality operates [11].

4.3. Comparison and Optimal AOA Determination

By analyzing the red and blue lines in Figure 1, it can be intuitively observed that although the optimal AOA at low and high speeds is still close to -2° , the tolerance for AOA deviation varies greatly. At 200 kilometers per hour, the AOA can be changed at a relatively large Angle without having a significant impact on fuel consumption. However, at 800 kilometers per hour, the curve is extremely steep, and even a slight deviation from the optimal flight posture can result in significant excess fuel consumption. This demonstrates that high-speed cruising must precisely control the operational requirements of flight to achieve maximum fuel economy. The results in the table clearly determine the best-performing AOA under each condition. At 200 kilometers per hour, the optimal fuel consumption is almost negligible, just as expected in low-power conditions. At 800 km/h, the fuel consumption is much higher, meeting the theoretical power requirement proportional to the speed cube (resistance \times speed). These values are in line with the order of magnitude results of the energy demand curves published in the FAA performance data and NASA technical reports. Even without direct experimental measurements, this protocol can still support the validity of the computational method [1].

4.4. Model Validation with NASA/FAA Data

The modeling results are consistent with NASA NACA 2412 data and FAA aerodynamic principles, enhancing the credibility of the model. This means that the low-speed mode allows for a greater AOA deviation, while high-speed cruising requires relatively more precise adjustments to enhance efficiency [1, 10].

5. Discussion

5.1. Interpretation of Findings

From the perspective of mechanical engineering, these results have multiple significances. Firstly, they confirmed that as one of the variables for evaluating fuel efficiency, it makes sense to choose to define whether AOA is related to it. Secondly, the results in the chart emphasize that energy efficiency research cannot uniformly handle the AOA effect under different flight conditions: low-speed and high-speed conditions require different analyses [4].

5.2. Engineering and Environmental Implications

Finally, they provide a practical basis for extending analysis to trajectory optimization or integrating AOA control into machine learning-based energy models for drones and commercial aircraft [15]. At 200 km/h, the sensitivity of fuel flow to AOA is the lowest. The best efficiency occurs at -2.3° , but the efficiency remains almost the same at nearby angles. At 800 km/h, the fuel flow rate is highly correlated with AOA, and the optimal AOA is -2.2° . Even a very small Angle of attack deviation can lead to a sharp increase in fuel consumption [1, 16]. The modeling results are consistent with NASA NACA 2412 data and FAA aerodynamic principles, enhancing the credibility of the model. This means that the low-speed mode allows for a greater AOA deviation, while high-speed cruising requires relatively more precise adjustments to enhance efficiency. These findings confirm that this study is of practical significance for exploring how to improve fuel efficiency and can serve as the foundation for further exploration of the optimal flight trajectories, fine-tuning strategies, and energy management frameworks in both manned and unmanned aviation.

5.3. Limitations and Future Work

Although this experiment has contributed to the study of aircraft, it inevitably has limitations that must be acknowledged. The modeling method is too simple, the data is too scarce, and the simulation framework does not apply particularly difficult aerodynamic principles. Not to mention that this experiment uniformly assumes stable horizontal flight and ideal conditions. The performance of aircraft in the real world is also influenced by other factors, such as atmospheric turbulence, engine degradation, nonlinear aerodynamic effects near stall, and the variation of air density with altitude. However, in this experiment, none of these have been taken into consideration for the time being. Although the complexity of these factors is beyond the scope of this study, it limits the applicability of the results to combat aircraft. Furthermore, the focus of the research was too narrow, with only one type of wing model being taken into consideration. Although this choice ensures the traceability of the verification experimental data, different airfoils or wing configurations may result in different optimal aircraft Angle of attack values or the shapes of the lines in the diagram [17]. Assuming that BSFC and propulsion efficiency remain constant across different speed ranges, this further simplifies the problem. However, during the flight of the aircraft, the parameters mentioned above will change significantly with the type of engine, throttle Settings, and more personalized Settings. Future work in this field should focus on improving the model by incorporating more wing styles and more parameter data, and wind tunnel experiments can also be added. Simultaneously focusing on improving multiple indicators can enhance fuel energy-saving efficiency, as well as strengthen the aircraft's stability, noise and emissions. If subsequent extensions of the same steps are conducted and analysis to different altitudes, flight trajectories, and engine-specific performance curves, etc., the experiment will provide more reliable insights. Finally, verifying the model based on flight test data is still of great significance for enhancing the applicability of experimental results.

6. Conclusion

The main findings of this study confirm that the angle of attack significantly influences fuel efficiency, with optimal values near -2.2° to -2.3° depending on flight speed. The results provide a replicable framework for integrating AOA optimization into flight trajectory planning, autonomous control systems, and sustainable aviation strategies. Future research directions include expanding the model to diverse airfoils and real-world conditions.

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