To what extent does angle of attack affect the lift-to-drag ratio of a NACA 4022 airfoil under subsonic flow conditions

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Abstract

Aerodynamic efficiency is an important part of aircraft design as it affects how well an aircraft can fly while keeping fuel use as low as possible. One way of measuring this efficiency is through the lift to drag ratio (L/D), which compares the amount of lift produced by an airfoil to the drag acting against it. A major factor that affects this ratio is the angle of attack (AOA), which is the angle between the chord line of the airfoil and the direction of the incoming airflow. Generally, increasing the angle of attack increases lift because a greater pressure difference develops between the upper and lower surfaces of the airfoil. However, drag also increases, meaning that a higher angle of attack does not always result in better performance. At larger angles, the airflow can also begin to separate from the upper surface, reducing lift and eventually causing the airfoil to stall. This research will use Computational fluid dynamics in ANSYS to investigate how changing the angle of attack affects the lift to drag ratio of a NACA 4022 airfoil under subsonic conditions. The airfoil will be tested at several angles of attack and the resulting lift, drag, pressure and airflow patterns will be compared. From these results, the study will aim to identify the angle of attack where the NACA 4022 operates most efficiently and explain why its performance changes as the angle of attack increases.

Key words: Airfoil, NACA 4022[1], Angle of Attack, Lift-to-drag ratio, subsonic flow, aerodynamic efficiency

Introduction

The aviation industry has become the pinnacle of modern day transportation. This is because it allows passengers and goods to be transported rapidly across large distances around the world. As technology within the industry has developed, engineers have attempted to improve aircraft performance whilst reducing cost of operations and fuel consumption. One of the most important factors influencing an aircraft's range efficiency is its aerodynamic performance. Small improvements in aerodynamic performance can reduce thrust required and hence, reduce fuel consumption. Due to this, the design and aerodynamic behaviour of the aircraft wings remains an important domain to investigate.

The cross-sectional shape of a wing, known as an airfoil, is one of the most critical factors in determining the aerodynamic performance of a wing. The difference in pressure and momentum change of the airflow as it passes over the airfoil creates aerodynamic forces. Two of the most important forces are lift and drag. Lift works roughly perpendicular to the direction of the incoming airflow, allowing the aircraft to overcome its weight, in other words the lift vector has a greater magnitude than the weight. Drag works roughly parallel and opposite to the direction of motion, opposing the aircraft as it moves through the air. The balance and variation between these forces influences the overall performance of the aircraft.

One method of measuring aerodynamic efficiency is the lift-to-drag ratio. This ratio compares the amount of lift generated by an airfoil with the drag produced. A larger lift-to-drag ratio indicates that an airfoil is producing comparatively more lift while generating less drag. Generally higher L/D ratios are linked to higher aerodynamic efficiency. Efficient lift generation can reduce the amount of thrust required to maintain flight, which can improve aircraft range and fuel efficiency as fuel consumption is reduced. The lift and drag produced by an airfoil depends on several parameters such as airfoil geometry, relative air velocity and angle of attack. Angle of Attack is the angle between the chord line of the airfoil and the direction of the relative wind. As the angle of attack increases the pressure distribution around the airfoil is usually changed and the magnitude of the lift and drag forces it develops is changed accordingly. By increasing at relatively low angles of attack, lift can be greatly increased . However, drag is also increased as the airfoil comes in contact with more incoming airflow. With large angles of attack, the flow separation can be more important and the aerodynamic efficiency of the airfoil may decrease as the airfoil is producing more lift.

This work relates solely to the NACA 4022 airfoil. Its aerodynamics will be analyzed using Computational Fluid Dynamics under subsonic flow conditions[1]. CFD allows the airflow around the airfoil to be simulated numerically and changes in pressure, velocity and aerodynamic forces to be observed without the need of a physical wind-tunnel model. By keeping the main simulation conditions constant and varying the angle of attack systematically, the influence of AOA on the calculated lift and drag coefficients can be calculated.

Methodology

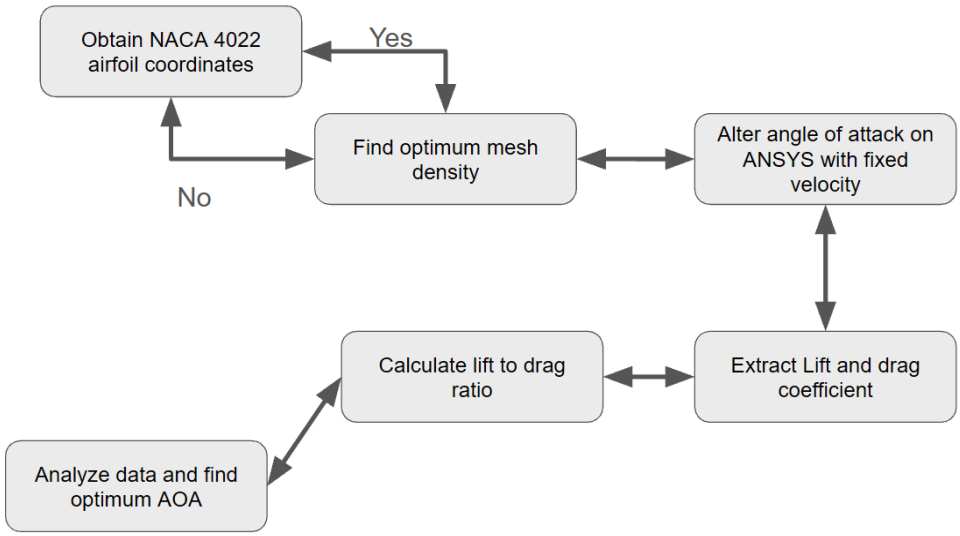


Figure 1: Methodology flow-chart

The figure above represents the consecutive stages followed throughout this investigation. Firstly, the NACA 4022 airfoil coordinates were collected and exported to Ansys[1]. The mesh sensitivity analysis was conducted and then maintained throughout the investigation while the

angle of attack was systematically altered. For each angle of attack the lift and drag coefficients were collected to calculate the ratio. The resulting values and ratios were then compared to determine how the aerodynamic efficiency can vary with angle of attack in order to find/identify the angle of attack with the highest lift to drag ratio.

Airfoil designing and meshing

The NACA 4022 airfoil was selected for this investigation to examine the effect of the angle of attack amendments on the lift to drag ratio and aerodynamic efficiency of the airfoil. This will be done under subsonic conditions. A series of coordinates that defined the upper and lower surfaces were imported into ANSYS, where points were connected to construct a 2D airfoil.

A C-shape mesh domain was created around the imported airfoil that consisted of a semi-circular region upstream and a rectangular region downstream. The area/domain was quite large so that the influence of outer boundaries close to the airfoil was reduced. As shown below[2]:

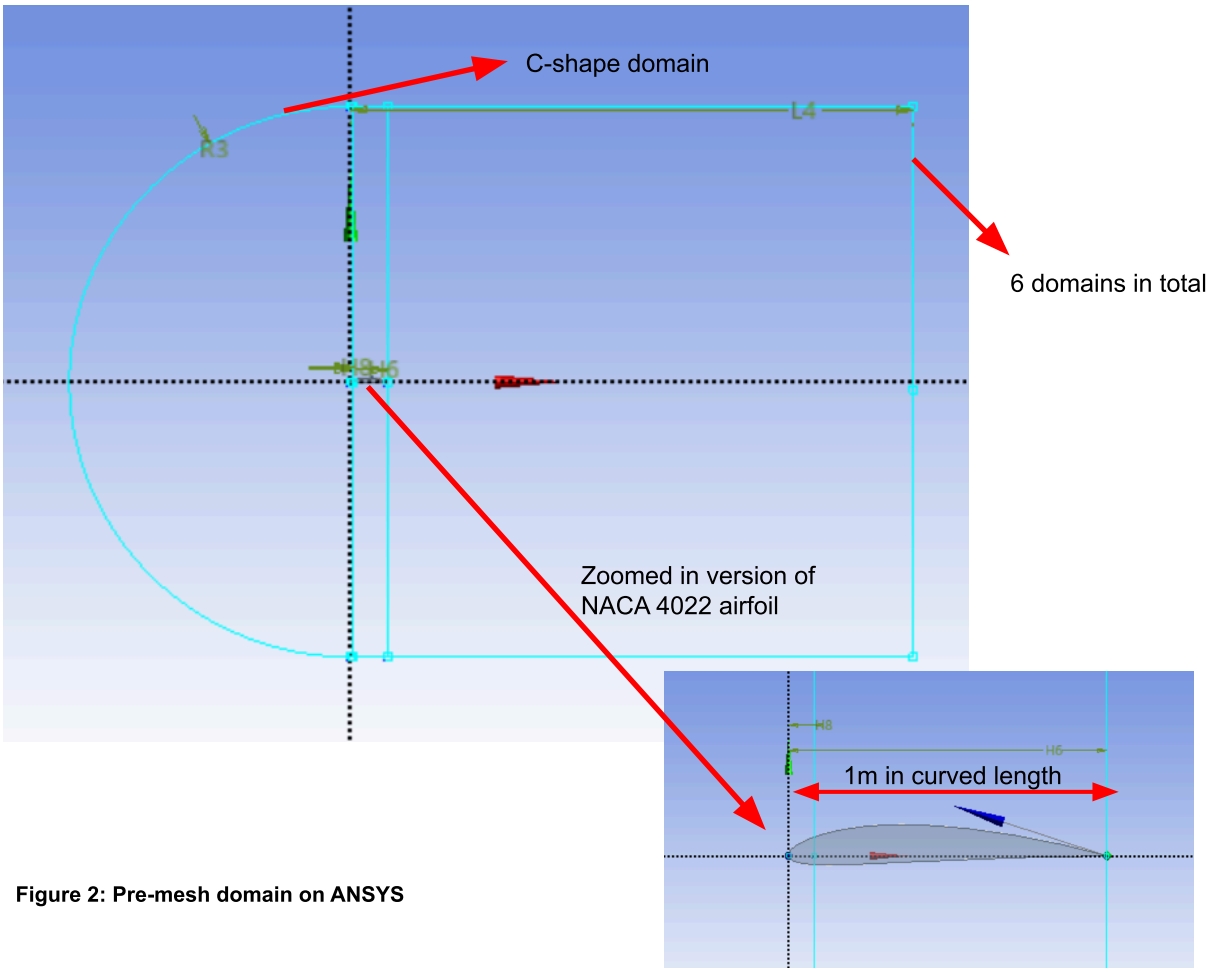


Figure 2: Pre-mesh domain on ANSYS

The domain subsequently went through meshing. Meshing is the process of dividing the air space around an airfoil shape into a grid of tiny individual cells so a computer can simulate airflow. There was a greater mesh refinement closer to the surface of the airfoil, leading edge, trailing edge. This is because larger changes in velocity and pressure were expected there. This also did allow the air flow behaviour near the airfoil surface to be represented more accurately. For each of the 6 domains a mesh division of 400 was chosen to balance aerodynamic accuracy with computational efficiency. A table was created to consider the effectiveness of mesh divisions.

Mesh division type	Aspect ratio	Numerical Diffusion error	Pros	Cons
Coarse (<150)	Chordwise spacing (Δx) is too large relative to the ultra-thin layer height (Δy)	High errors cause steep pressure gradients, especially at high AOA or critical AOA	• Fast • Low RAM usage • Useful for initial boundary condition testing	• Overpredicts lift and drag values
Optimal (300-500)	Keeps grid skewness and orthogonal quality within recommended limits.	Error drops below 1%	• Factors in the Leading edge pressure gradients as AOA varies. • Standard Academic range	• Higher setup time
Ultra-fine (>800)	Streamwise spacing becomes unnecessarily small	Minor and negligible performance benefits from 300-500	• Highly detailed wake propagation simulation in solver.	• Hardware constraints • Excessive simulation run times.

Lift and drag calculations

Lift and drag were used to evaluate the ratio and aerodynamic performance of the NACA 4022 airfoil. Lift acts almost perpendicular to the direction of relative airflow, while drag acts approximately parallel and opposite to the airflow **[3]**.

The coefficients of lift and drag can be modelled as:

$$C_{Lift} = \frac{L}{\frac{1}{2}pv^2A}$$

And drag:

$$C_{Drag} = \frac{D}{\frac{1}{2}pv^2A}$$

L = lift force
D = drag force
p = Air density
v = velocity of air
A = surface area incident of airflow

The aerodynamic efficiency can be determined using the lift to drag ratio, in order to determine the most optimal lift to drag ratio**[3]**.

$$\frac{L}{D} = \frac{C_L}{C_D}$$

A higher lift to drag ratio means that greater aerodynamic efficiency exists as a larger amount of lift is being generated relative to the drag produced. Lift and drag can also be represented on an airfoil model shown in Figure 3:

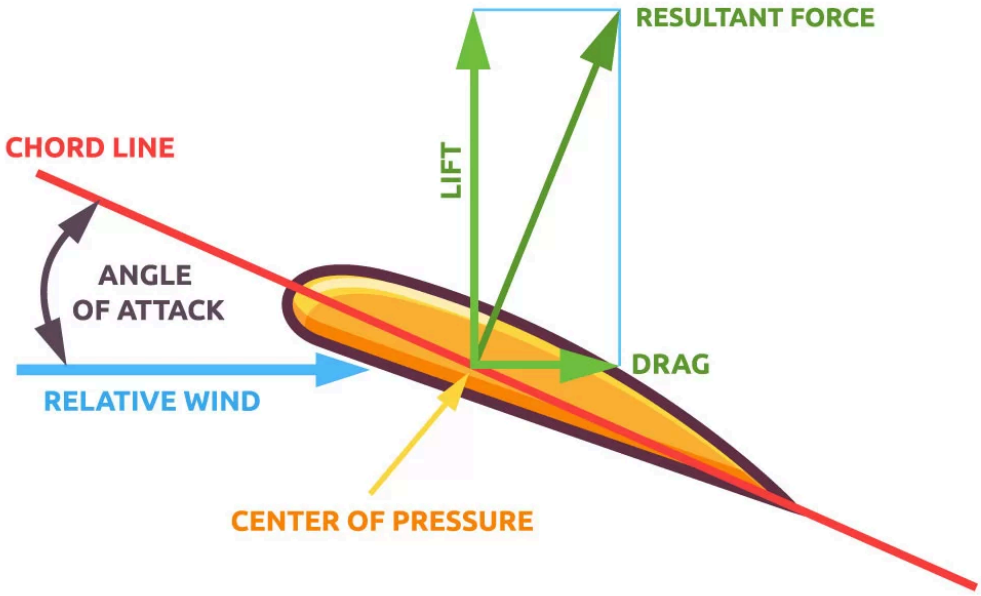


Figure 3: Airfoil annotated diagram

Angle of Attack(AOA) analysis

The angle of attack is the angle between the chord line of the airfoil and relative airflow. In this investigation, the angle of attack was independent and was systematically altered in ANSYS. And the airfoil, velocity, and mesh density were kept constant.

Angle of attacks ranged from 0 to 16 degrees. And increments were done in 2 degree intervals. For each value the direction of incoming airflow was adjusted by changing the horizontal and vertical components of velocity, while maintaining a constant total velocity. These components can be expressed as**[4]**.

$$V_{x-air} = Vcos(\theta)$$
$$V_{y-air} = Vsin(\theta)$$

V represents the magnitude of the velocity of air and theta represents the angle of attack.

The resulting angle of attack will be plotted against a $\frac{C_L}{C_D}$ graph to get a visual idea of the relationship between the 2 variables. This graph will permit us to find the maximum lift to drag ratio and therefore determine the operating condition of the NACA 4022 airfoil which demonstrates the greatest aerodynamic efficiency.

Operating conditions

$$V_{air} = 48.8\, ms^{-1}$$
$$C_{length} = 1.00m$$
$$\rho_{air} = 1.225\, kgm^{-3}$$
$$\mu = 18.1 \times 10^{-6} Pa\, s$$
$$T = 15°C = 288.15K$$
$$P = 1013.2\, hPa = 101320\, Pa$$

From the data the Reynolds number can be calculated. The Reynolds number used to predict whether fluid flow in a given situation will be laminar or turbulent. The Reynolds number can be calculated as shown below.

$$Re = \frac{\rho_{air} V_{air} c_{length}}{\mu} = \frac{(1.225)(48.8)(1)}{(18.1 \times 10^{-6})} = 3.3 \times 10^{6}$$

Mesh

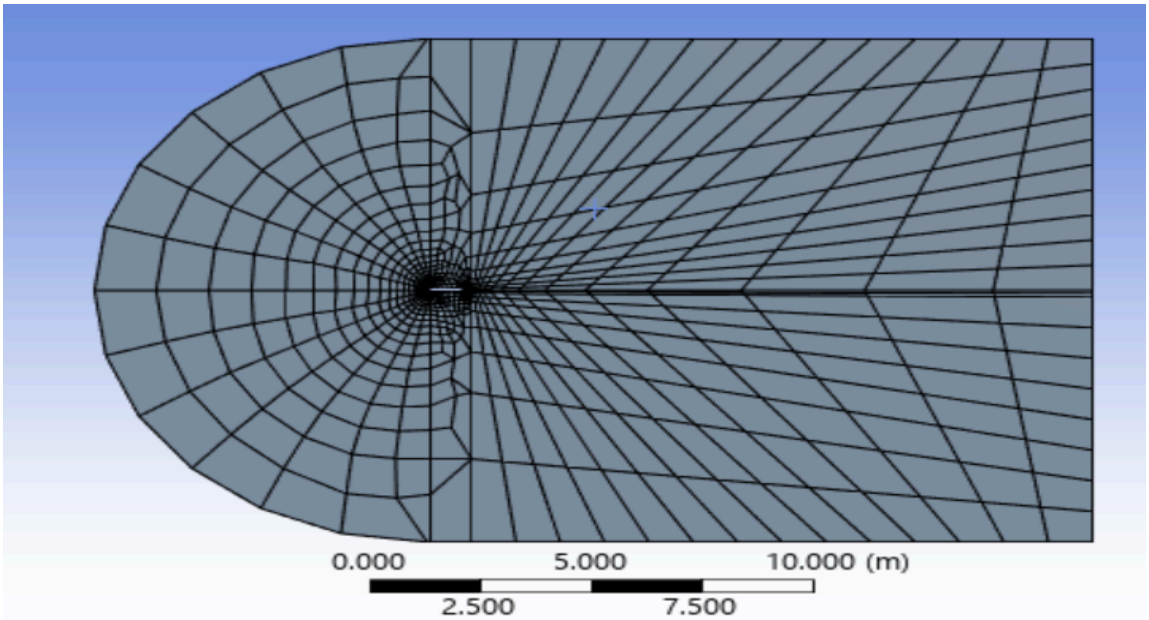


Figure 4: mesh before simulation

Figure 4 shows the mesh that will be used in the correlation testing between AOA and lift to drag ratio under subsonic conditions. Unfortunately, the meshing was impacted by system performance and the mesh density is not very high. There are 1089 individual elements in this mesh, which is less than the desirable range of 11,000 to 14,000. Therefore results may not be entirely accurate as the mesh refinement around the leading and trailing edges of the airfoil would not allow for better resolution of high-gradient regions, particularly in areas prone to boundary separation and turbulent air.

Results

Angle of attack analysis

The table below presents the aerodynamic coefficients used to investigate the expected relationship between angle of attack and aerodynamic efficiency and lift to drag ratios under subsonic conditions.

AOA	C_L	C_D	$\frac{C_L}{C_D}$
0	0.43	0.011	37.9
2	0.64	0.012	51.4
4	0.84	0.014	59.9
6	1.05	0.017	62.8
8	1.25	0.021	60.0
10	1.43	0.029	49.5
12	1.56	0.044	35.8
14	1.60	0.070	23.0
16	1.49	0.114	13.1

As seen in the table above, the lift and drag ratios initially increase as the angle of attack increases. Between 0 and 2 degrees, the L/D ratio increases from 37.8 to 51.37, indicating an increase of 35.6%. The ratio is continuing to increase until a maximum value of 62.8 at 6 degrees. Compared to 0 degrees, thai represents an increase of 65.8%.

The increase in aerodynamic efficiency at lower AOA's occurs due to the lift coefficient increasing faster than the drag coefficient. This is seen from 0 to 6 degrees as the lift coefficient increases from 0.43 to 1.05. This is an increase of around 145%, whereas the drag coefficient increases only from 0.011 to 0.017. Secondly, the additional lift generated at high angles of attack outweighs the corresponding drag effects on aerodynamic efficiency.

After 6 degrees the trend doesn't stay constant. Although the lift coefficient continues to increase between 6 and 14 degrees, the drag coefficient begins to increase at a faster rate. More specifically, at 10 degrees, the lift coefficient reaches 1.43 white the drag coefficient increases to 0.029, reducing the ratio to 49.5. This is also seen as the angle tends towards 14 degrees.

The greatest reduction occurs towards the upper angles such as between 14 and 16 degrees. At this angle, the coefficient of lift decreases from 1.6 to 1.49 while the coefficient of drag increases from 0.070 to 0.114. This causes the aerodynamic efficiency to reduce and consequently, the lift to drag ratio falls further from 23.0 to 13.11. This behaviour stays consistent with increasing flow separations from the boundary layer at high AOA's; Therefore, additional increases in AOA no longer produce proportional increases in lift, but drag increases substantially and at a faster rate.

Overall, there is a non linear relationship between angle of attack and lift/drag ratio. Aerodynamic efficiency improves until 6 degrees and subsequently reduces until 16 degrees. Therefore under subsonic conditions, approximately 6 degrees represents the optimum angle in the given operating conditions.

Graphical representation of AOA vs L/D ratio

The graph for AOA vs L/D is plotted below:

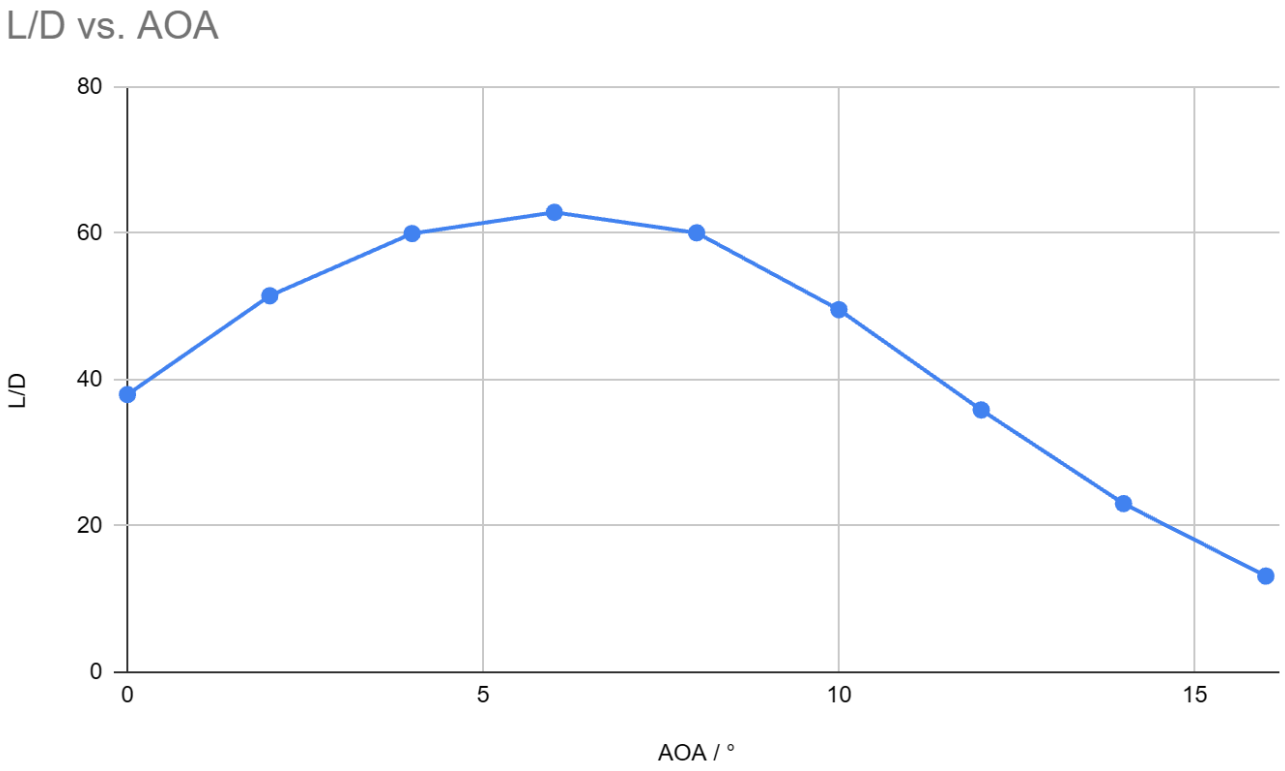


Figure 5: L/D vs AOA graph

Figure 5 shows there is a rapid increase in the L/D ratio until 4 degrees before the curve reaches a maximum at 6 degrees, with a ratio of 62.8. Beyond this point the L/D ratio begins to decrease, where the decrement becomes more pronounced at angles above 10 degrees. By 16 degrees, the ratio is at a minimum, around 79% below its maximum value. Therefore the shape of the curve shows that increasing AOA only improves aerodynamic efficiency to a certain optimum value, not for the entire list of AOA values.

Looking into the nature of the graph and linking it to the airfoil, will help analyze why the graph behaves in this way. At lower angles of attack, the airflow is largely attached to the surface of

the airfoil. Increasing the AOA, increases the pressure difference between the upper and the lower camber of the airfoil, allowing lift and drag to rapidly increase. This explains why the L/D ratio initially improves until 6 degrees. However as the AOA becomes larger, the pressure gradient, especially on the upper surface is highly unfavorable. Therefore the airflow loses momentum and has a reduced ability to stay attached to the surface of the airfoil as seen in the image below.

As the flow separation increases, a larger area of turbulent air or wake develops behind the airfoil, resulting in an increase in pressure and drag. Simultaneously, the separated airflow reduces the effectiveness of the low pressure region of the upper camber, meaning that further increases in AOA will generate smaller increases in lift. This occurs until the airfoil approaches the critical angle of attack, and a stall occurs. Therefore the reduction in the L/D ratio beyond the optimum angle occurs due to drag increasing at a faster rate than lift. This explains why the relationship is not linear as below the optimum AOA, increasing the AOA improves aerodynamic efficiency, but above it; aerodynamic efficiency is reduced and boundary separation is more prominent.

Lift & drag coefficient analysis

A separate analysis can be conducted between the coefficient of lift & drag and AOA respectively to look at their individual variations.

Looking at the dynamic pressure equation from the lift force formula:

$$q = \frac{1}{2}\rho_{air}V^{2}_{air}$$

Where $\rho = 1.225\ kgm^{-3}$, $V_{air} = 48.8\ ms^{-1}$, substituting values gives:

$$q \approx 1458.6\ Pa$$

And for a 1m chord in a 2D modeler, the lift and drag force per metre can be displayed as:

$$L_{F/D} = qcC_{L}$$
$$D_{F/D} = qcC_{D}$$

The table below shows the effect of AOA on the lift coefficient and the lift force per metre of airfoil length. Values for the lift force have been substituted in from the lift force per metre formula: $L_{F/M}$

AOA	C_L	Lift force Nm^{-1}
0	0.43	627
2	0.64	933
4	0.84	1225
6	1.05	1532
8	1.25	1823
10	1.43	2086
12	1.56	2275
14	1.60	2334
16	1.49	2173

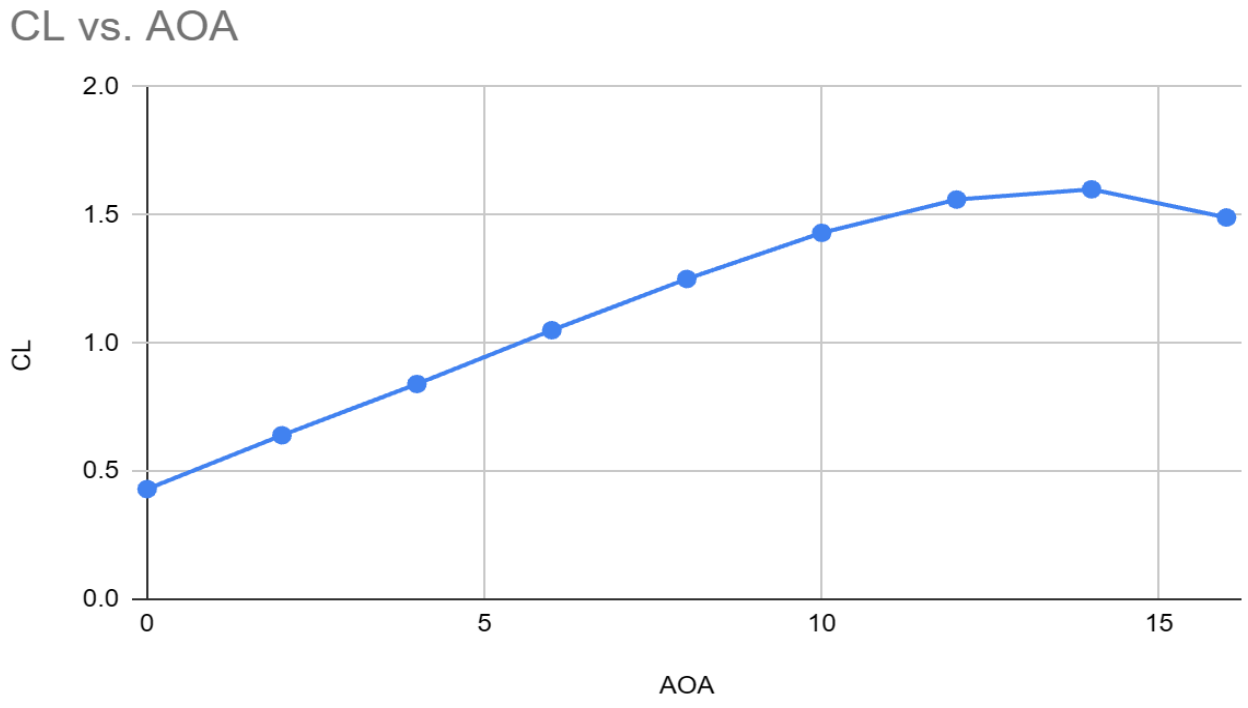


Figure 6: Coefficient of lift vs AOA graph

Figure 6 above shows that the lift coefficient has a linear correlation to AOA, which is different from the concavity of the curve as seen in the L/D ratio and AOA. The linear trend is also evident in the lift force per unit wing span, which increases from 627Nm^-1 at 0 degrees to a maximum of 2334Nm^-1 at 14 degrees. This shows that at the same velocity of the relative airflow; increasing the angle of attack shows a large increment in the vertical force of the airfoil.

An important feature of the graph is that the maximum lift occurs later than the maximum L/D ratio or maximum aerodynamic efficiency. The airfoil continues to generate lift beyond the 6 degree optimal angle where the L/D ratio was the highest. This represents the fact that increasing the angle of attack is a beneficial method when the objective of the airfoil is to increase lift., even though the overall efficiency is reducing. From a practical perspective, an aircraft needs to operate at a higher AOA when producing more lift is necessary, certain scenarios can include maintaining level flight at low speeds or during approach.

We can also analyse the lift behavior from a force perspective by looking at the Lift per metre section of the table above. Zooming into a particular instance, the reduction in lift from 2334N/m at 14 degrees to 2173 N/m at 16 degrees is quite significant as it shows that increasing AOA does not always lead to an increase in lift production. This particular behaviour is due to the substantial flow speciation on the upper camber of the airfoil at high AOA's. Once a significantly large portion of the upper camber flow separates, the low pressure region at the upper camber becomes weaker, causing the coefficient of lift to reduce and leading the lift force to reduce at 16 degrees.

Drag coefficient analysis

The table below dictates the variations of drag coefficient and drag force per unit wing span with respect to angle of attack.

AOA	C_D	Drag force(N/m)
0	0.011	16.0
2	0.012	17.5
4	0.014	20.4
6	0.017	24.8
8	0.021	30.6
10	0.029	42.3
12	0.044	64.2
14	0.070	102.1

16	0.114	166.3

Using the data from the table an individual drag coefficient vs AOA graph can be plotted.

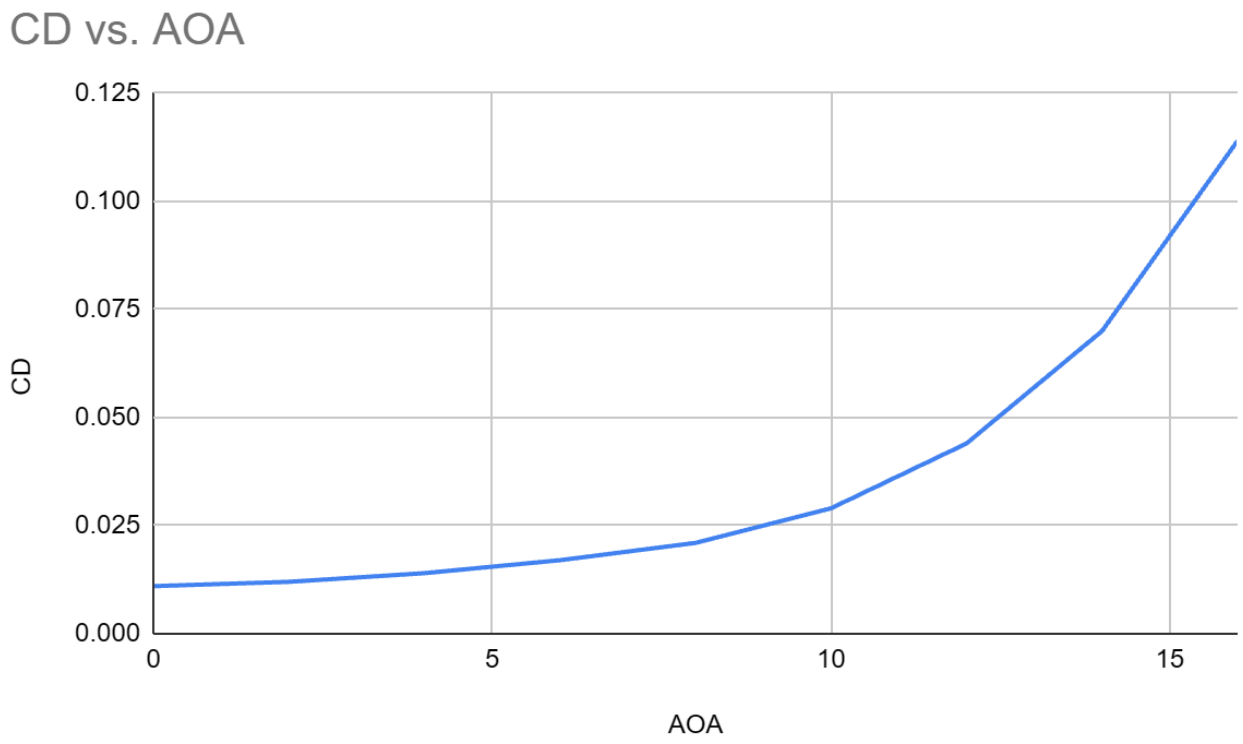


Figure 7: Coefficient of drag vs AOA graph

From the graph we can see that the aerodynamic implications of increasing AOA are low at small angles, for example between 0 and 6 degrees the drag force only increases by 8.8 N/m. Comparing this to angles between 10 and 16 degrees, drag increases from 42N/m to 166 N/m, this is almost a 400% increase between 6 angles.

This rapid increase occurs because the pressure distribution varies as angle of attack changes. At low AOA's the airflow can follow the boundary layer of the airfoil surface quite closely. On the contrary, at higher angles the pressure gradient on the upper surface becomes very steep, making it increasingly difficult for the boundary layer airflow to flow downstream the airfoil. As the boundary separation progresses, the wake behind the airfoil becomes wider as is present in a larger volume of air. Secondly, the pressure on the rear section of the airfoil is reduced

compared to the forward facing surfaces, such as the leading edge. Therefore, the resulting pressure imbalance creates a greater increase in induced drag as induced drag is a byproduct of lift.

Looking at the practical implications of this scenario; in steady flight, the aircraft's propulsion system must provide a minimum amount of thrust to overcome the drag at high angles of attack. Thus, an increase in drag from 24.8 N/m at 6 degrees to 166.3 N/m at 16 degrees would require a significant increase in thrust to maintain the same airspeed and level flight. Hence, this illustration shows why a high AOA is aerodynamically inefficient even before the complete stall.

Discussion and Conclusion

In this study, the separate force calculations have demonstrated how and why the optimum L/D ratios do not occur at the angle producing the maximum lift. The optimal L/D ratio is at 6 degrees but the angle with the greatest lift is at 14 degrees. Hence drag is a penalty of an increase in lift production. Across these 2 angles, we can also see a 52% increase in lift force and an increase of more than 300% for the drag force.

This investigation was able to examine the extent to which AOA affects the lift to drag ratio of the NACA 4022 airfoil under subsonic conditions. The analysis displayed that the AOA has a high but non-linear influence on the L/D ratio of an airfoil. At low AOA's, increasing the angle improved the L/D ratio as lift increased proportionally faster to drag. The higher ratio was 62.8 at an AOA of 6 degrees. After this point, the aerodynamic efficiency or L/D ratio was progressively decreasing as the drag coefficient began to increase faster than lift.

The particular behaviour of the lift coefficient helps explain the first part of the relationship. The coefficient of lift increased from 0.43 at 0 degrees to a maximum of 1.60 at 14 degrees. At lower AOA's, increasing the AOA increases the pressure difference between the upper and lower cambers of the airfoil, hence resulting in greater lift. Therefore we can see the approximate linear correlation between lift coefficient and AOA until 12 degrees. After 12 degrees, the airfoil had reached a position where increasing boundary layer separation was starting to inhibit lift production.

Drag had followed a different path. At lower AOA's, the drag coefficient increased by a small amount. Beyond 8 to 10 degrees, the drag coefficient bag rises much faster. As the AOA increases the pressure gradient on the upper camber becomes increasingly stronger, making it harder for the boundary layer airflow to remain attached. The separated region and wake turbulence behind the airfoil become larger and increase induced drag. This explains why the L/D ratio can decrease while the lift coefficient is still increasing.

Significance to the field

The results have several impacts on the aerospace field. The L/D ratio is an important measure of aerodynamic efficiency because it represents how much useful lift can be generated for a given amount of aerodynamic resistance. An aircraft operating near the angle corresponding to maximum L/D ratio requires less thrust to overcome drag for the amount of lift being generated.

This can contribute to lower fuel consumption, greater range and improved overall aircraft efficiency.

In the perspective of the NACA 4022 airfoil, the 6 degree AOA shows significantly favourable operating conditions compared to the maximum AOA of 16 degrees. These findings highlight key considerations for wing design, where aerospace engineers must evaluate both overall lift generation and the efficiency of the lift production. Selecting an improper operational angle of attack risks raising thrust demands and fuel usage, even when the airfoil yields substantial lift. The results also represent why different AOA's are used at different points during the flight. For example, during cruise periods maintaining a relatively low angle of attack is beneficial as it provides an optimum relation between lift and drag as speed will be maximised. On the other hand, in scenarios where greater lift production is needed such as takeoff or landing phases, a higher AOA may be needed due to the increase in parasitic and induced drag.

Limitations

There were several limitations to the investigation that could be changed when conducting it in the future. Firstly, the CFD setup used laminar flow despite the Reynolds number being 3.3×10^6. At this number, the airfoil would expect to experience boundary-layer transition and turbulent flow over at least part of its surface. Using a fully laminar flow simplifies the aerodynamic behaviour and may affect the predicted drag and separation characteristics. A future investigation could use a transition-capable or turbulence model, such as the $k - \omega$ SST model to provide a more realistic representation of the airflow.

The second limitation was the mesh was quite coarse due to limited computational ability. Even though the mesh concentrated elements around the airfoil and the flow region, greater refinement would have been beneficial near the leading, trailing edge and the airfoil surface. This would have provided more accurate data of the pressure and velocity gradients. This limitation is significant for drag calculation as drag is highly sensitive to near-wall and near-Cshape flow behaviour. Therefore, a more refined mesh with an additional boundary layer inflation would increase the reliability of the calculated lift and drag coefficients.

Lastly, the investigation maintained a freestream velocity of 48.8m/s. This means that the results for the lift/drag coefficients and lift/ drag force are only under 1 Reynolds number condition. To avoid this, different velocities, temperatures could alter the Reynolds number and can shift the angle of attack at which the stall occurs and has the maximum lift to drag ratio. Furthermore, repetitions of the investigation can be done across several Reynolds numbers to determine whether the optimum AOA remains consistent or not.

Authorship & Acknowledgements

Sidharth Ahuja: Writing - Conceptualization, Methodology, Lead Author. **Nikhil Paliwal**: Writing - Conceptualization, Supervision, Review & Editing.

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