Computational Aerodynamic Analysis of A Light Sport Aircraft: Calculate Its Angle Of Attack Required During Take-off

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Abstract. The present work reports an aerodynamic analysis for a specific type of light sport aircraft (LSA) called Aurora SA60L. This research focuses on the range of angles of attack the plane can fly safely in the take-off stage. To achieve this target, a computer-aided design (CAD) model of the aeroplane is built and put into computational fluid dynamics (CFD) to simulate its aerodynamic performances. Some detailed calculations of force balance are introduced to quantify the plane's safety condition. The result successfully gets the range of angles in take-off conditions.

Keywords: light sport aircraft, Computational Fluid Dynamics, single-slotted flap, aerodynamics.

1. Introduction

The Light Sport Aircraft (LSA) is a type of fixed-wing propeller-driven aircraft with a piston engine. It has some important advantages, such as less fuel consumption, low maintenance cost and easy to control, so it is extensively used for pilot training. However, the take-off procedure of the LSA is still dangerous for novices. Accordingly, designers and engineers need to make this stage as safe as possible. Because pilots sometimes pull the joystick harshly at low speeds, an appropriately designed LSA should be able to take off at a low speed in a flying attitude of a large angle of attack with no occurrence of stalling. To accomplish this aim, a high-lift device called flap is commonly used in LSA designing. This ancillary device attached to the trailing edge of a wing is movable equipment controlled by pilots to change the geometry of the wing section. When the flap is deflected downwards, it can increase lift force dramatically. The single-slotted flap, which is always used in LSA design, can provide a considerable amount of lift force, much more than that of plain flap and split flap.

This study aims to figure out the relationship between the lift and drag forces with respect to the different angles of attack during the take-off stage of the LSA. To do so, one type of the LSA named Aurora SA60L, which is commonly used in China for pilot training, is employed for the research. During take-off, the single-slotted flap is conventionally deflected at an angle of 15 degrees for SA60L. Besides, a NACA0012 airfoil with a design of a single slotted flap is used, as it is widely used in LSA manufacturing [4]. Additionally, the Computational Fluid Dynamics (CFD) is used to test the aerodynamic performances of the airfoil, because it is a cheaper way compared with doing experiments by means of wind tunnel.

In the present day, the CFD plays an indispensable role in aerodynamics. In theoretical analysis, based on some theorems such as the conservation of momentum, variables including velocity and pressure along the flow can be expressed as a function of position and time. Then the flow is divided into a series of discrete points with certain positions and time. After connecting these points to constitute grids using the CFD meshing process, these grids are treated as a set of finite volumes. As the position and time of the grids are known, dependent variables such as the pressure of these grids are known as well. After integrating these grids' data, the pressure distribution along the airfoil is known, so a part of the lift and drag force can be calculated. Briefly speaking, with suitable theoretical models and meshes, the CFD can analyze the lift and drag force quickly and accurately.

In this research, a CFD application called Ansys Fluent is utilized. Additionally, the Reynolds-averaged Navier-Stokes (RANS) equations combined with the Mentor shear stress transport (SST) k-ω model is implemented, because this is an accurate method for analyzing airfoils in low Mach

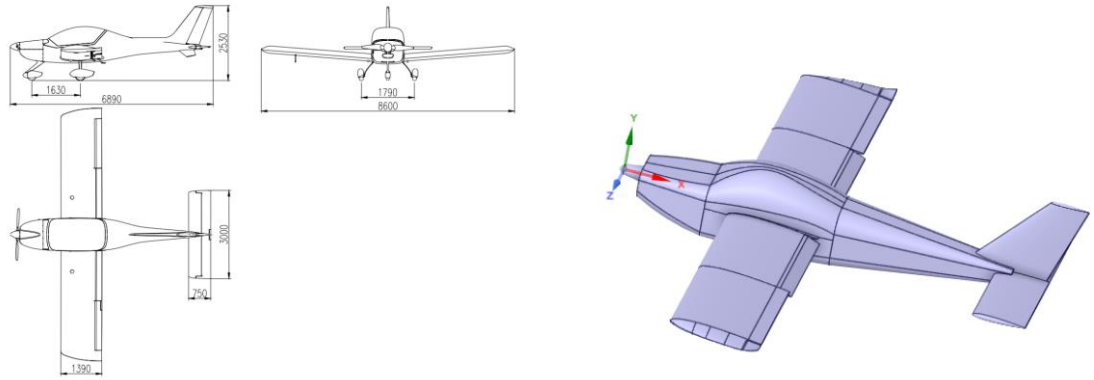
number airflow (Ma<0.3). It is also worth mentioning that a computer-aided design (CAD) model is built to do simulation in CFD. The model is drawn and assembled in an application called CATIA.

2. Methodology

To get reasonable results, an aeroplane model is drawn in Catia. By putting this model into Ansys Fluent, CFD's results of aeroplane's drag and lift for different angles of attack can be obtained. In a critical situation which is the airplane can merely maintain its position and velocity without falling, the aeroplane is in an equilibrium state during the take-off procedure. This state has a relationship between the angles of attack and the lift and drag force. Consequently, the range of angles of attack in taking off can be obtained.

2.1. CAD Model

The SA60L is a single propeller engine, low wing, two-seater LSA. Some paramount parameters are shown in Table 1, and a three-dimensional view of the SA60L is shown in Fig. 1a. As a result, a CAD model can be built as illustrated in Fig. 1b.



(a) (b)

Fig. 1 (a) A three-view drawing of SA60L, dimensions are in millimeters [2]. (b) The SA60L airplane with flaps deflected at 15 degrees

In addition, a 3D NACA 0012 airfoil model is used in this research as shown in Fig. 2 [4]. It is also modified to add a single-slotted flap. The deflection angle, gap and overlap are three important parameters for flap design. The deflection angle of the flap is the angle between the chord line of the retracted airfoil and the deployed flap. The gap between the flap and the airfoil is defined as the minimum distance between the slot-lip and the flap, and it is assumed to be 0.01 chord length [9]. The overlap, which is defined as the horizontal distance between the slot-lip and the flap's leading edge, is 0.069 chord length [8].

Table 1. Some geometric features and aerodynamic performances of SA60L [2].

Name	Dimension
Wingspan	8.6 m
Mean aerodynamic chord length	1.39 m
Aspect Ratio (AR)	6.2
Flap's area	0.57 m2
Flap's chord length	0.33 m
Maximum power	73.5 kW
Minimum take-off speed	85 km/h
Airplane's maximum mass in take-off	600 kg
Estimated centroid from leading edge	450 mm

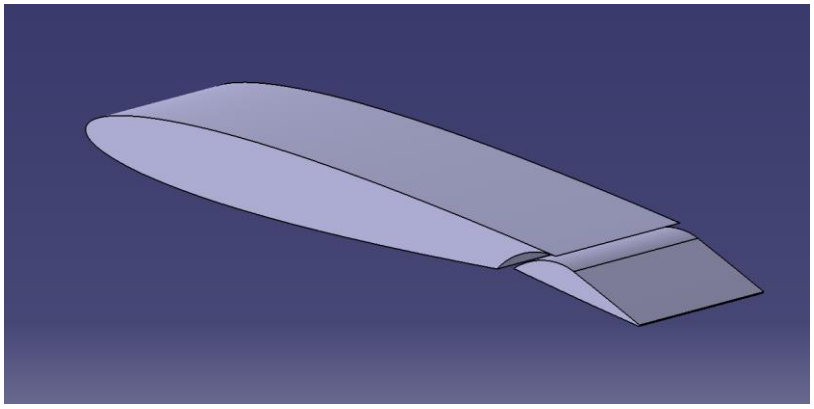


Fig. 2 NACA 0012 with a slotted flap at a deflection angle of 15 degrees

2.2. Theoretical analysis

2.2.1. Force balance

In take-off, the maximum power is used, so the thrust force is the maximum power of the airplane divided by the velocity of the airplane.

$$T = \frac{P}{V}$$

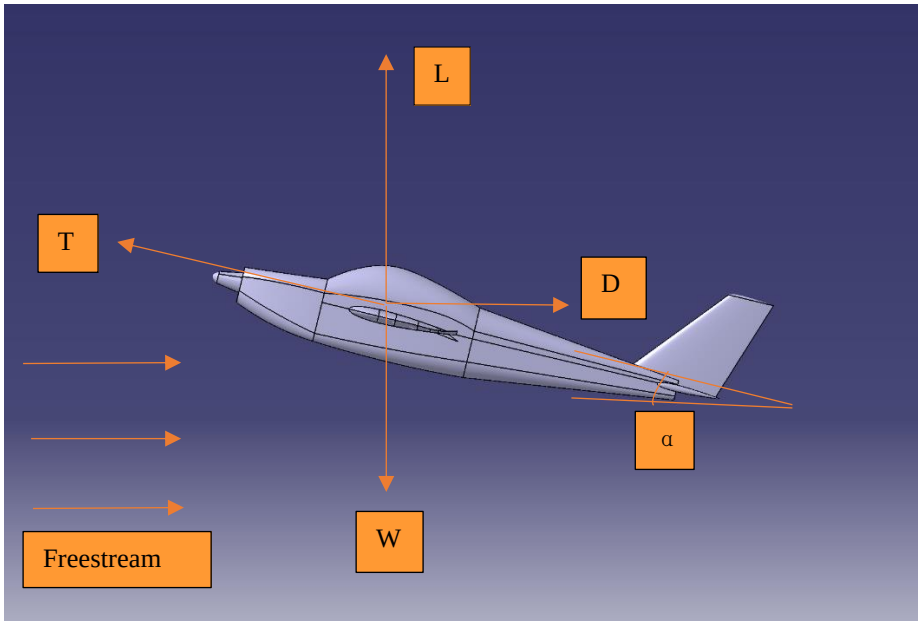


Fig. 3 The free body diagram of the aeroplane

Where T is the thrust force, P is the power generated by the engine, and V is the velocity of the airplane. In the real world, the velocity of the airplane is not equal to the speed of airflow from freestream exactly, as there exists a gap called wind speed. However, it is a requirement that a light plane cannot take off in windy weather. For example, the plane is not allowed to take off in tailwind conditions with a wind speed of 2 m/s [2]. Besides, the upwind condition can increase the lift force dramatically, so it is not treated as a critical condition. In turn, the difference between the velocity of the airplane and that of the airflow is negligible. In this research, the speed of airflow would be used as the freestream velocity.

To avoid fall in the take-off procedure, the thrust and lift force in the vertical direction should be larger than the weight of the airplane, and the thrust in the horizontal direction should be no less than the total drag force, otherwise, the speed of the airplane decreases, which can cause a decrease in the lift, as the lift is proportional to the speed of airflow. To simplify the questions, it is reasonable to

assume that the critical situation during take-off is when all the vertical forces are balanced. As shown in Fig. 3, according to the free body diagram, the equation can be written as

$$\frac{P}{V}\sin(\alpha) + L \geq W$$

Where α is the angle of attack, L is the lift force, and W is the weight of the airplane. The maximum weight of the airplane is when it is fully loaded (600 kg), which is 5886 N.

In the meantime, the horizontal force should be greater than 0 N, otherwise the speed of airplane would decrease, which leads to a decrease in lift force as well, so the equation can be deduced as

$$\frac{P}{V}\cos(\alpha) \geq D$$

Where D is the total drag force

Pilots sometimes pull the joystick too much, which means the angle α might be too large to take off to cause the flow separation. To satisfy both conditions of taking off successfully and ensure the α as large as possible, the lift force is required to be large while the thrust is no less than the drag force. Both requirements must be satisfied to ensure the airplane is in a safe condition during the take-off phase.

2.3. CFD simulation

The airfoils and flaps are modelled in Catia as mentioned in Section 2.1, then they are imported to Ansys Fluent to analyze their aerodynamic performances. Additionally, there are some pre-processing steps that need to be taken before the analysis.

2.3.1. RANS and SST k-ω model

Although turbulent flow is so complicated that even computers cannot analyze the flow properties precisely for a long time, engineers are satisfied with the time-averaged properties in practice. Subsequently, the Reynolds-averaged Navier-Stokes (RANS) formulation can be used. In such a way, flow variables like velocity can be decomposed into time-averaged velocity and local oscillations of velocity. However, the local oscillations have too many unknown terms. To solve this problem, the transport equation is taken into consideration. The Menter shear stress transport (SST) k-ω model is a combination of two models. It uses the standard k-ε model in the region far from the wall and the k-ω model in the region near the wall. Until now, it is a suitable method for analyzing airflow passing an airfoil [3].

2.3.2. Boundary conditions

The freestream velocity is the velocity required to take off, which is 85 km/h according to regulations [2]. The difference between the actual freestream velocity and the speed of airplane is explained in Section 2.2.1. Returning to the subject, as this speed is much less than the sound speed in atmospheric conditions (Ma≈0.067<<0.3), the airflow can be treated as incompressible flow [1].

This research focuses on the take-off procedure, and the SA60L normally fly within 400 meters from the ground, so the standard atmospheric data for pressure, temperature, air density and viscosity are used. These are 101,325 Pa, and 293.15K, so the viscosity of air is 1.8*10-5 kg/(m*s), and the density of air is 1.2 kg/m3 [9].

2.3.3. Meshing

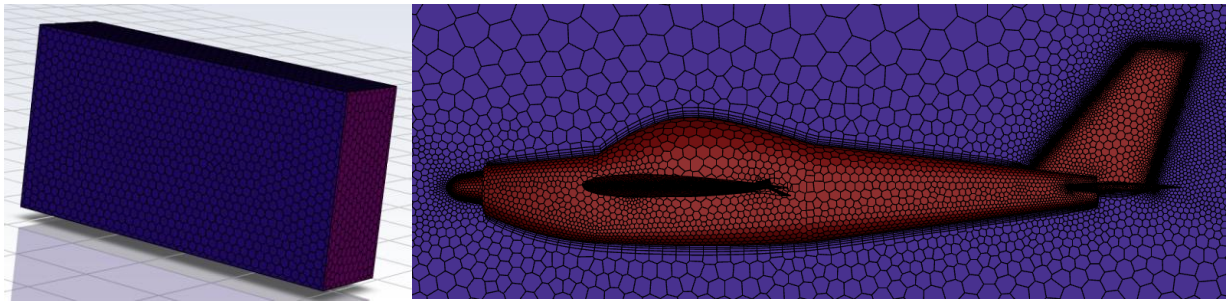
The airfoils and flaps are analyzed based on a rectangular computational domain. Although the C-type domain can ensure a better flow separation using making the curvature of the grid match the leading edge of the airfoil [5], it needs more CPU to get results. The domain dimensions are related to the chord length (c) of the airfoil as shown in Table 2 and Fig. 4a. In addition, the model is symmetrical, so doing a symmetry in Fluent can reduce a significant number of calculations and time.

After creating a proper domain, the meshing is required. In this part, computer memory is limited, so a CFD analysis should use as little computer memory as possible to get accurate results. Accordingly, based on Section 2.3.1, the analysis is required to be highly concentrated on the

boundary layer of the airfoil, while the outer region of the boundary layer can be treated as an ideal flow to some extent [1]. In turn, as shown in Fig. 4b, the meshing grids around the aircraft are small and dense, and the grids outside of the inner circle are relatively sparse and coarse. It is worth noting that leading edges, trailing edges and corners of airfoils and flaps should be much denser than other areas. On the side, the non-slip condition is used in this research. The number of boundary layers can be up to 100 to get precise results, but using 5 layers is satisfied for a LSA at low speed. The maximum skewness is 0.94328, which is a bit lower than 0.95, so the meshing quality is merely acceptable [6]. There are some ways to improve the quality, such as adding the number of boundary layers and bodies of influence around the flap and edges of the airfoil. However, taking the limited CPU into consideration, these improvements are not used in this research.

Table 2. Some main parameters of the meshing

Name	Dimension
Inlet	5c
Outlet	15c
Number of boundary layers	5
Number of cells	117,8898
Maximum skewness	0.94328



(a) (b)

Fig. 4 (a) Asymmetrical domain for an airfoil with flap deflection of 15 degrees. (b) Meshing for a SA60L with flap deflection of 15 degrees

2.3.4. Solver Set-up

After settling the domain and meshing grids, it is time to set up. The solver is pressure-based. The density of air is a constant value under atmospheric conditions. The inlet velocity is the speed of the airplane. As mentioned before, the Menter SST k-ω model is used in this research. It is noteworthy that the second-order upwind scheme is selected because of its better performance when the results converged [6,7]. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm which is used in this research is suitable for incompressible, low-speed analysis [3]. Most other settings are defaults by Fluent. After the setup part in Fluent is finished, the program can run by itself.

3. Result and discussion

3.1. Result

After running program in the Fluent, the results are shown in Table 3. By substituting these results into equations in Section 2.2.1, it can be found that the angle of attack between 29 degrees to 30 degrees can make sure the aircraft has enough lift force against weight and the drag force is no larger than the thrust in drag direction so that the plane can maintain its speed rather than decrease. However, it is not realistic to ask pilots adjust the angles of attack within one degree in flying. Subsequently, the required velocity for take-off is the minimum speed to take-off, if pilots cannot control the aircraft perfectly, the velocity of take-off should increase to a larger number, such as 100 km/h.

Table 3. Total lift forces, total drag forces and total forces balance for different angles of attack (minus means the drag or the weight is larger than the forces trying to counterbalance them)

Angle of Attack (degrees)	Total lift force (N)	Total drag force (N)	Total force along lift's direction (N)	Total force along drag's direction (N)
0	933	150	-4953	2963
5	2700	250	-2915	2851
10	3400	616	-1945	2450
15	3754	1120	1326	1887
20	3900	1640	-921	1285
25	4200	2240	-370	581
26	4300	2400	-221	398
29	4340	2600	-37	123
30	4400	2742	70	-46
35	4600	3350	500	-800

Pilots who fly the SA60L usually pull the joystick to leave the runway at a higher speed rather than 85 km/h, and they intend to keep at a certain height and angles of attack to get a higher forward force to increase airplanes' speed before they pull up the joystick to increase height.

According to Table 4, even though not all the angles of attack are calculated, it is certain that from 15 degrees to 20 degrees, the aeroplane can maintain its safety condition. Consequently, during take-off, it is strongly recommended pilots increase the speed of the aeroplane up to 100 km/h on the runway when fly SA60L.

Table 4. Total lift forces, total drag forces and total forces balance for different angles of attack, and the take-off velocity set up to 100 km/h

Angle of Attack (degrees)	Total lift force (N)	Total drag force (N)	Total force along lift's direction (N)	Total force along drag's direction (N)
10	4742	840	-685	1766
15	5220	1560	19	996
20	5448	2254	467	232
25	5770	3020	1002	-622

3.2. Discussion

Although results are reasonable because they coincide with real experiences, there are still some problems in this research as shown below.

1. The model in Fig. 1b is not built precisely. Some dimensions of the SA60L airplane are not included in Fig. 1a, such as the curvature of the aeroplane's canopy. In other words, Fig. 1a is a rough three-view drawing. Besides, as shown in Fig. 1b, even though the landing gear and propellers only have limited effects on the total lift force and drag force, they are not negligible for a precise simulation. In addition, wings' stabilizers have a huge impact on the forces, but pilots normally do not use them or set up them in a position that can counterbalance the unsteady force caused by wind, so they are neglected as well. Moreover, when the plane is in the take-off stage, the horizontal tail wing is in an upward direction rather than keeping parallel alongside the fuselage. However, if the airplane is close to stalling, the alarm in the SA60L will start to ring, pilots are trained to release the joystick at that time in flying schools, so it is reasonable to assume the horizontal tail wing is parallel to the fuselage in the critical situation.

2. The CFD simulation is not precise in this research. Firstly, the enclosure (domain size) in CFD is not large enough. Ideally, the enclosure size can be 10-20 times the fuselage's length. However, the CPU of the computer used in this research is limited, so the enclosure is much smaller than the ideal enclosure. Thus, the maximum skewness is a bit large (0.94), so that the results are not perfectly converged, as shown in Fig. 5. Besides, in this research, the density is a constant value with no heat

conduction. Although the Mach number is much less than 0.3, the density of air can still change a bit, which can influence the results eventually. Again, this is for simplifying the calculations and iterations to reduce the workload of the computer. Moreover, when the angles of attack increase from 0 degrees to 20 degrees, results become hard to converge with the same iteration number (300). In other words, the results of large angles of attack are not as accurate as the results of small angles of attack.

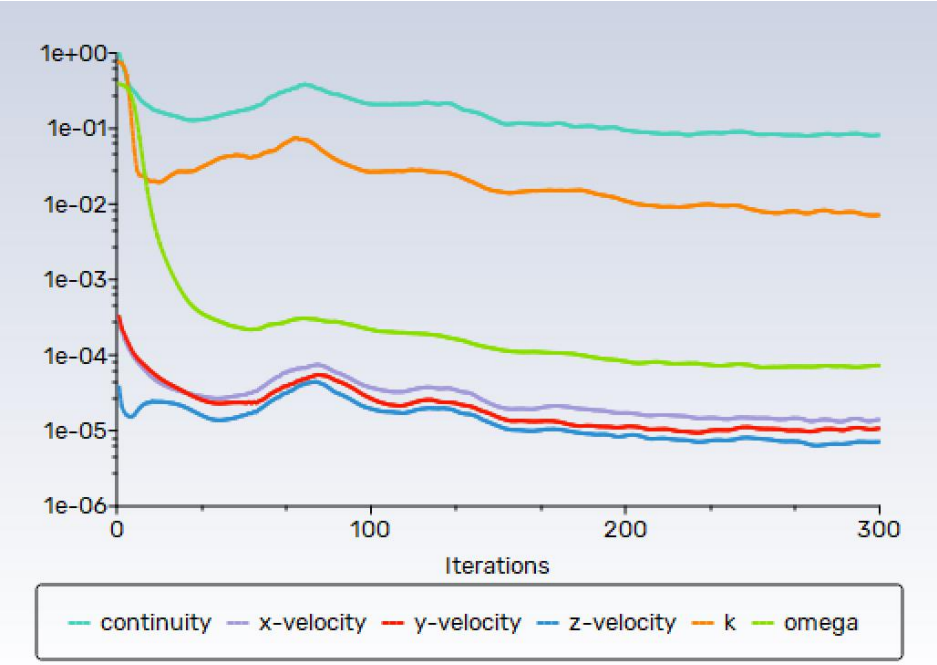


Fig. 5 the residuals of CFD simulation for the SA60L at 20 degrees of angle of attack and 85 km/h

3. Theoretically, the force balance can be achieved even in the stalling condition. In contrast, the plane starts to vibrate and rattle when its angle of attack is close to the stalling angle. Thus, the equilibrium state mentioned in Section 2.2.1 is an ideal but not realistic condition. The force balance is hard to achieve.

4. The centroid of the aeroplane is another complicated problem. Based on the SA60L specification [2], the centroid of the aeroplane is 0.39 m to 0.49 m from the trailing edge of the wings. In this research, the centroid is simplified to be 0.45 m from the trailing edge, and it is in the middle of the aeroplane along the wingspan's direction. However, if the aeroplane is in the take-off process, fuel and luggage would move backwards to change the position of the centroid. For this two-seat aeroplane, if there is no copilot, the centroid along the wingspan will change as well.

5. Calculations about wing load are out of concern in this research, but if the wing load exceeds the designed wing load, the aeroplane will crash.

As shown in Section 3.1, the lift and drag are sensitive to the angle of attack, and to take off safely, the angle can only be adjusted within 2 degrees, which makes it impossible for most pilots to control the plane so precisely. As a result, the taking-off speed of the aeroplane should increase from 85 km/h to a higher speed.

4. Conclusion

After drawing a three-dimensional aeroplane model in Catia, the CFD approach is used to compute the aerodynamic performances of a light sport aeroplane for different angles of attack. Thus, the range of angles of attack at which pilots can pull during take-off can be obtained, which is from 29 degrees to 30 degrees at 85 km/h. If the angle of attack is larger or less than this critical angle, the take-off procedure would fail. There are some ways to avoid this dangerous situation, such as increasing the take-off speed to 100 km/h.

However, the model and the CFD approach are simplified. For example, the model does not contain landing gear parts and stabilizers. The skewness of the meshing is about 0.94, which causes the simulation cannot converge perfectly. In turn, the angles in Section 3.1 are not the same as the angles in the real world exactly. Besides, CFD is one way to evaluate the aerodynamic performance of the aeroplane, theoretical analysis and experiment are other two indispensable ways to understand the performance. By combining these three cornerstones, a more pilot-friendly LSA can be invented.

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