

Aircraft Design Analysis, CFD and manufacturing

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Abstract. Aircraft design, manufacturing and CFD analysis as part of aerodynamic course, the students achieve sizing from a conceptual sketch, select the airfoil geometry and the tail geometry, calculate thrust to weight ratio and wing loading, use initial sizing and calculate the aerodynamic forces. The students design their aircraft based on the geometrical dimensions resulted from the calculations and use the model to build a prototype, test it in wind tunnel and achieve CFD analysis to be compared with the experimental results. The theory of aerodynamic is taught and applied as a project based. In this paper, the design process, aircraft manufacturing and CFD analysis are presented to show the effect of project based on student's learning of aerodynamic course. This project based learning has improved and accelerated students understanding of aerodynamic concepts and involved students in a constructive exploration.

The analysis of the aircraft resulted in a study that revolved around the lift and drag generation of this particular aircraft. As to determine the lift and drag forces generated by this plane, a model was created in Solidworks a 3-D model-rendering program. After this model was created it was 3-D printed in a reduced scale, and subjected to wind tunnel testing. The results from the wind tunnel lab experiment were recorded. For accuracy, the same 3-D model was then simulated using CFD simulation software within Solidworks and compared with the results from the wind tunnel test. The values derived from both the simulation and the wind tunnel tests were then compared with the theoretical calculations for further proof of accuracy.

Keywords: computational fluid dynamics (CFD), design, aircraft, aerodynamic, wind tunnel

1. Introduction

The conceptual design phases begins a conceptual sketch and aims to determine key design parameters that the final aerodynamics will have to meet. This design will typically include the approximate wing and

tail geometries, fuselage shape, and the internal locations of major components such as the engine, cockpit, payload/passenger compartments, landing gears, and fuel tanks. These design requirements are used to estimate the weight of the final aircraft by comparison to previous designs. The takeoff weight is a critical characteristic that will dictate the final size and shape of the airfoil. Iterative calculations for this weight are made using assumptions from previous aircraft designs and aerodynamic AIAA table standards^[1, 4, 5, and 7]. The final lift requirements will then determine required airfoil size and shape, with more iterative refinements made between steps.

Gennaro Zuppari shows that an interactive and wholly automatized computer code has been developed on a microcomputer for the aerodynamic analysis of airfoils in incompressible flow fields, it is intended to serve as a useful support in teaching aerodynamics. The code contains a number of modules (or blocks) for: (1) drawing the shape with the help of an interactive graphic device interfaced with the microcomputer; (2) computing the aerodynamic inviscid and viscous flow field and the aerodynamic coefficients; (3) modifying and/or correcting the body shape and then computing the new aerodynamic coefficients^[6]. Mark Drela presents some of his views on teaching fluid dynamics and aerodynamics that the course syllabus stresses physical and mathematical understanding of underlying concepts rather than specialized engineering or computational skills, it

is argued that deep understanding is what enables the engineer or researcher to generate truly new ideas and work on out of the ordinary topics and to continue personal learning and development throughout a career^[3, 7].

The goal of this paper and its research is to show the students the steps of aerodynamic design and perform their own design and compare three types of acquired lift results for their own designed aircraft. Following proven aerodynamic formulas and AIAA airfoil charts, assumptions were made to provide a baseline weight from which the iterations were run to refine the final design weight. This finalized weight was then used to calculate the geometry of the wings, fuselage, airfoil, and tail section of the aircraft. This geometry was used to model the complete aircraft in computer aided design software and a 1:584 scale model was 3D printed for wind tunnel testing. The wind tunnel was used to measure lift and drag forces for various angles of attack that could then be compared to both the iterative calculations as well as the results calculated through computational fluid dynamics.

2. Design Analysis Methods

2.1 Phase #1 theoretical calculations

The theoretical calculations is a useful method as to further define the usage of the aircraft. These calculations will give an idea of the basic structure to the design team. Properties that are highly important to a newly designed aircraft are directly resulted from this stage of design. The design team will use this tool to determine the range and weight limitations of the aircraft. Before the modeling phase a type of wing will be selected and further refined in later phases of design.

The design weight was calculated by taking the weight of everything that was part of the plane and adding it all together. This was used to initially calculate the weight to be used for the design.

$$W_0 = W_{crew} + W_{payload} + W_{fuel} + W_{empty}$$

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - \left(\frac{W_f}{W_0}\right) - \left(\frac{W_e}{W_0}\right)}$$

The empty weight was calculated in accordance with the W_0 guess weight in order to iterate with the calculated design weight. By using multiple iterations the design weight could be narrowed down to one true value.

Empty Weight Fraction

$$W_e/W_0 = 0.23 * W_{o(guess)}^{-0.5} * 1000$$

The recalculated empty weight fraction was used with the intention of recalculating the design weight. Which would be the final weight that would be used in the design. This was necessary for not only recalculating the design weight but also the fuselage.

Recalculated Empty Weight Fraction

$$W_e/W_0 = \left(a + b * W_0^{c_1} * A^{c_2} \left(T/W_0 \right)^{c_3} \left(W_0/S \right)^{c_4} M_{max}^{c_5} \right) K_{VS}$$

The recalculated design weight was taken in order to calculate the final design weight used in the design using the recalculated empty weight fraction. This formula is also used to determine the value of the recalculated fuselage length.

Recalculated Design Weight

$$W_0 = W_{crew} + W_{payload} + \left(W_{fuel}/W_0 \right) W_0 + \left(W_e/W_0 \right) W_0$$

Fuselage Length

$$L_f = 0.23 * W_0^{0.5}$$

Fuselage Area

$$S_f = \left(\pi * d_f^2 / 4 \right)$$

Span

$$b = \sqrt{AR * S}$$

AR is an aspect ratio which is the ratio of its length to its chord. A low aspect ratio indicates short, stubby wings while a high aspect ratio indicates long narrow wings. This equation is used to determine the

true aspect ratio. The length of the wing span is determined using the aspect ratio and is also vital to the geometry and design of the aircraft. It's determined by taking the square root of the product of the aspect ratio and area of the wing. The wing area is also a vital component to the design of the aircraft, calculated by simply multiplying the wing thickness by the span.

Wing Area

$$S_{wing} = \text{Wing thickness} * b$$

The horizontal tail is required in any plane for flight. With the fuselage and wings accounted for the design of the tail is all that is missing. The horizontal tail is determined by multiplying 0.1 by the thickness ratio.

Lift forces contrast with the drag force and is the component of the force of a fluid flowing past the aircraft perpendicular to the oncoming flow direction. The lift and forces were determined at different angles of attack from 0 to 15 degrees.

The first priority of testing was to render a three dimensional representation of the proposed design using Solidworks. Using the calculated dimensions for the fuselage. Following the fuselage, the wings needed to be modeled. The airfoil chosen for the aircraft was the NACA 2415. Using the calculated values for span, chord lengths (root, mean, and tip), mean chord span, one wing was modeled and then mirrored in Solidworks for consistency throughout the entire wing span, as shown in table 1 and Figure 1.

Table. 1 Aircraft Dimensions

DESCRIPTION	VARIABLE	VALUE	UNITS
FUSELAGE LENGTH/FUSELAGE DIAM	L_f/D_f	8	
FUSELAGE DIAMETER	D_f	28.375	ft
FUSELAGE AREA	S_F	632.34	ft ²
WING AREA	S_{wing}	9100	ft ²
AIRCRAFT WETTED AREA	S_{wet}	18653	ft ²
HORIZONTAL TAIL	HT	29.208	ft

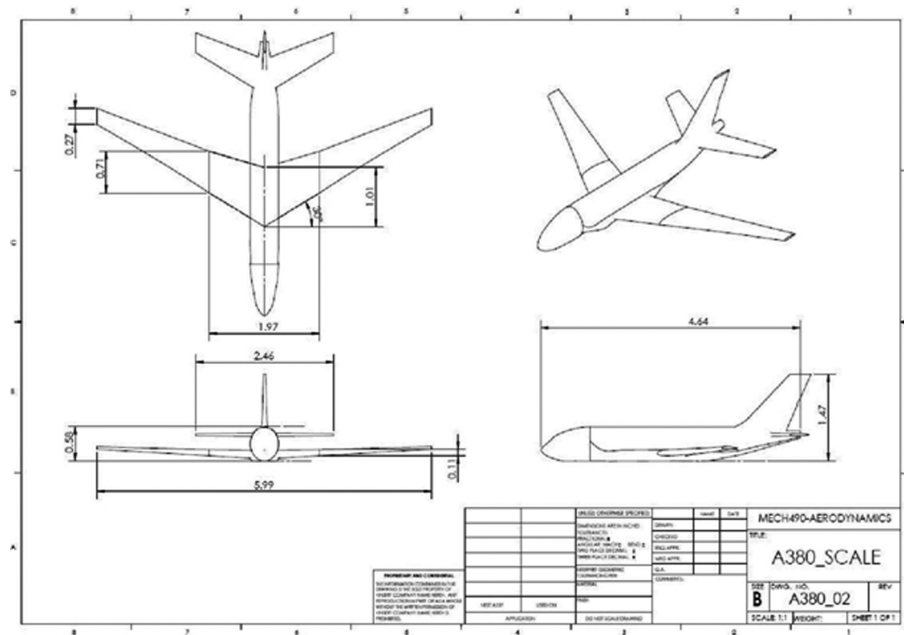


Fig. 1 Solid works model of aircraft

3. PHASE #2 wind tunnel laboratory experiment

Upon completing all parts of the aircraft, they were assembled together to produce the final model of the proposed aircraft (as shown in Figure 2). This model was scaled down 1:585 in order to print it using the uPrinter 3-D printer located in the Manufacturing Center at Wentworth Institute of Technology. The material that the model was printed with was ABSplus Plastic



Fig. 2 The 3D printed model

4. PHASE #3 CFD simulation

A CFD study in the Solidworks program paralleled the experimental wind tunnel analysis. The same conditions were reproduced within the program. The exact same scaled model was also studied. As to

ensure accuracy each study was performed independently and uninfluenced by one another. The model created in the Solidworks program was then prepared for simulation. The meshing function of the simulation proved to be highly instrumental in attaining accurate results from the CFD. Figure 3 shows the contour of the pressure and figure 4 shows the streamlines of air around the aircraft.

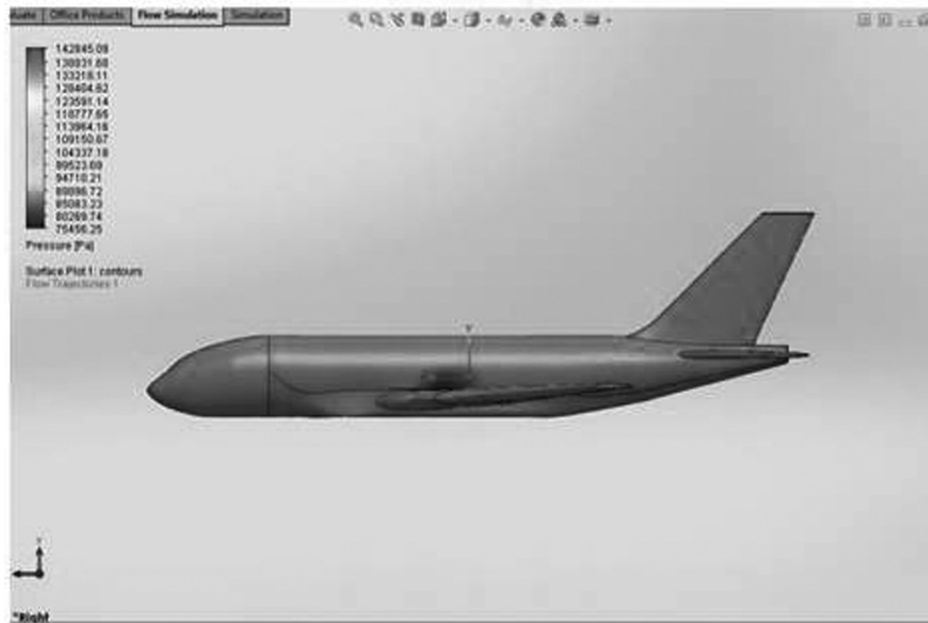


Fig. 3 The pressure contour of the airplane

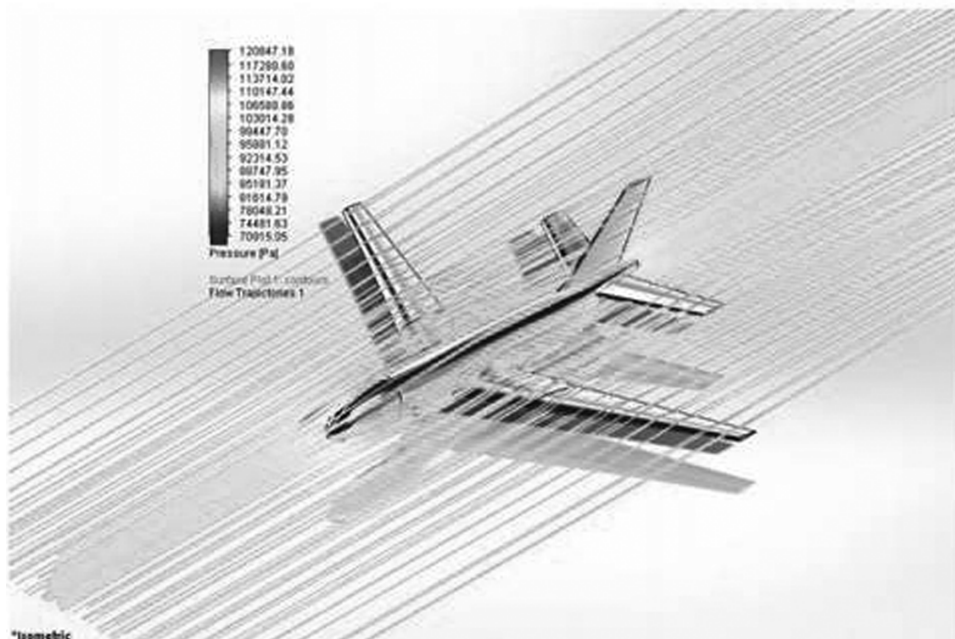


Fig. 4 The streamlines of the air around the airplane

The comparison between the experiments and the CFD simulation has been carried out as shown

in Figures 5 and 6. At low angle of attack the difference between the experiments and CFD is slightly significant comparing to high angle of attack for both drag and lift forces. Parasitic drag in the CFD simulation was not indicative of what we found in the theoretical calculations. Further refinement of this model would likely reduce the percent difference observed, although not by much. In contrast, the lift percent error ranged from only 38 to 91% which is quite good considering the many assumptions made. Overall, a trend can still be seen in these two sets of data: a positive correlation between drag and lift as a function of angle of attack. As angle of attack increases, so do both drag and lift. This makes sense because as the plane pitches up more surface area is in contact with the flow, causing more drag. But at the same time, the increased angle of attack on the airfoil creates a greater pressure drop because the air moves faster over the top of the wing, attributing to more lift. This trend carried over to the comparison between the CFD and wind-tunnel tests of the 1:585 scale model. Teams were made aware that the wind tunnel would not be a very accurate measurement tool. It was not designed to simulate the conditions the project required, nor were the 3D models perfect representations of the CFD models. Despite these truths, percent error for both lift and drag fell between 6.56 and 99% for both the 22.5 and 29.7 mph wind tunnel trials. Given the circumstances, these results were considered successful, as they still provide a valid representation of angle of attack's effects on both lift and drag on aircraft. In retrospect, more could have been done to reduce the gross percent errors that were experienced during the design process, primarily in testing equipment and procedure, but the concepts applied would remain the same. The three phases of design and assumptions that were made based on the A380 produced somewhat reasonable lift and drag results for the designed aircraft's aerodynamics. Table 2 shows the comparison of the results of drag and lift forces.

Table 2 Simulation and wind Tunnel

Angle	Wind Tunnel Results		CFD Results	
	Drag (N)	Lift (N)	Drag (N)	Lift (N)
0	0.2220	0.1780	0.1610	0.0032
4	0.2740	0.2180	0.2400	0.0693
8	0.3240	0.2330	0.3150	0.1095
12	0.3160	0.2480	0.4900	0.1663
15	0.3950	0.2560	0.4114	0.1954

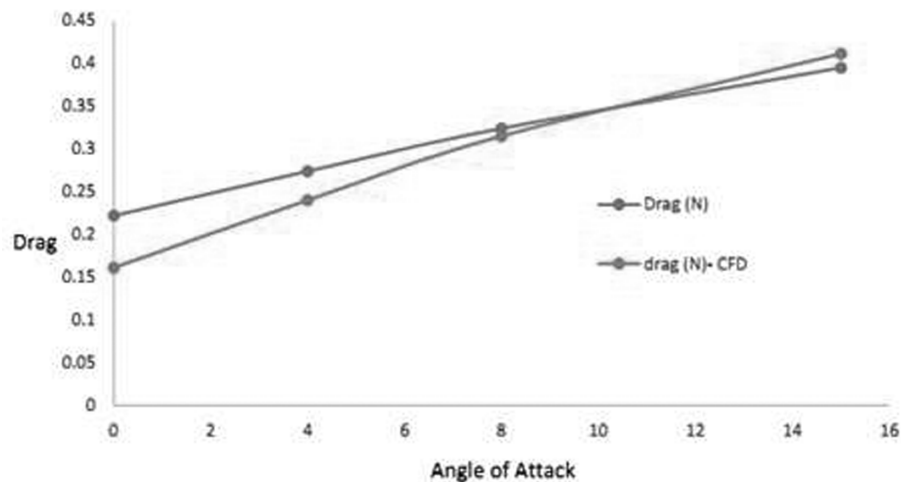


Fig. 5 Comparing Drag-experiment and CFD vs. angle of attack

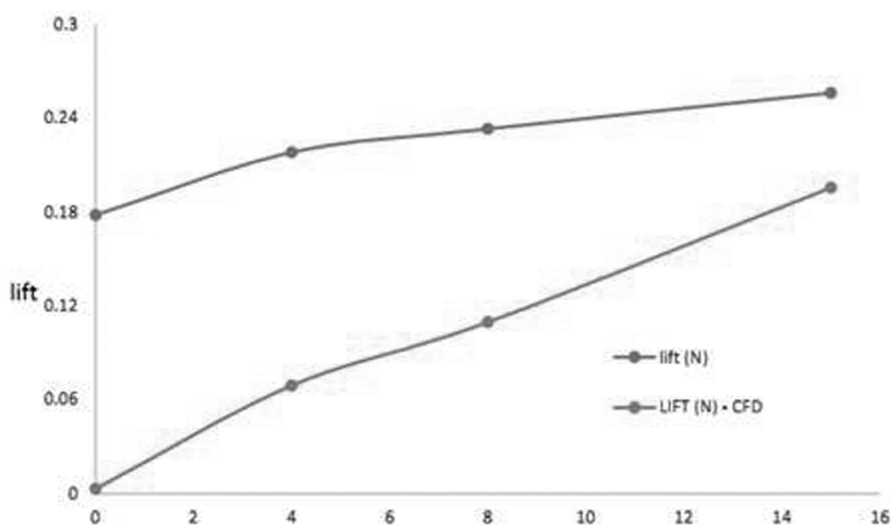


Fig. 6 Comparing Drag-experiment and CFD vs. angle of attack

5. Conclusion

The three phases of design were critical in following a set design procedure, and using the assumptions to make reasonable estimates for our own model. While these assumptions assisted in moving the design along, they greatly contributed to the errors we would see between our different data trials: the theoretical manual calculations, CFD simulation, and scale model wind tunnel test. These various paths allowed us to better understand different means of data acquisition for airfoils, and helped affirm validity in our design process.

Overall, a trend can still be seen in these two sets of data: a positive correlation between drag and lift as a function of angle of attack. As angle of attack increases, so do both drag and lift. This makes sense because as the plane pitches up more surface area is in contact with the flow, causing more drag. But at the same time, the increased angle of attack on the airfoil creates a greater pressure drop because the air moves faster

over the top of the wing, attributing to more lift.

It is concluded that this project-based learning has improved and accelerated students understanding of aerodynamic concepts and involved students in a constructive exploration

E	-	Endurance
R	-	Range
C_{Cruise}	-	Specific Fuel Consumption
C_{Loiter}	-	Loitering Specific Fuel Consumption
V	-	Cruise Velocity
L	-	Lift Force
D	-	Drag Force
W_{empty}	-	Average Weight Empty
W_{Crew}	-	Average Weight of Crew
$W_{Payload}$	-	Average Weight of Payload
W_{Max}	-	Average Maximum Weight
L_f	-	Fuselage Length
S_f	-	Fuselage Area
S_{wing}	-	Wing Area
S_{wet}	-	Aircraft Wetted Area
S_{HT}	-	Horizontal Tail Area
HT	-	Horizontal Tail
L_{ww}	-	Wing Weight
q	-	Dynamic Pressure
C_{Lmax}	-	Max Lift Coefficient of Wing
C_L	-	Lift Coefficient of Wing
C_l	-	Lift Coefficient of Airfoil
AR	-	Aspect Ratio
b	-	Wing Span
T	-	Thrust

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