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Analysis for Effect of Angle of Attack on Coefficient of Lift of Wing Structure

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Abstract

Dimensional optimization has always been a time-consuming process, especially for aerodynamic bodies, requiring much tuning of dimensions and testing for each sample. Aerodynamic auxiliaries, especially wings, are design dependent on the primary model attached, as they influence the amount of lift or reduction in drag which is beneficial to the model. This study aims to reduce the time period taken to finalize the design parameter for the same. For a wing, the angle of attack is essential in creating proper splits to incoming winds, even under high velocities with larger distances from the separation point. In the case of a group of wings, each wing is then mentioned as a wing element, and each wing is strategically positioned behind the previous wing in terms of its vertical height and its self-angle of attack to create maximum lift. At the same time, its drag remains variable to its shape ultimately maximizing the C_L/C_D ratio. A high value of C_L indicates a significant component of horizontal drag is converted into a vertical lift. While the value of C_D remains variable to different design factors, adjusting the angle of attack can minimize the drag forces caused by reducing the frontal area of impact. In this study two winged elements were considered for the front wing. Three parameters with 5 levels each were used for the parametric optimization. Twenty-five sets of setup designs were considered as a part of the Taguchi optimization study. The C_L/C_D ratio of X_5 model obtained by CFD analysis is 15.78 and by experimental testing is 15.32. It is found that the C_L /C_D ratio obtained by Numerical analysis and Experimental investigation are well corroborated.

Introduction

The field of fluid mechanics underwent a revolution in the 1960s with the advent of computer-based simulation. It is necessary to solve, with minimum simplification, the whole set of equations regulating the conservation of mass, momentum, and energy in a fluid. Currently, using all three of the aforementioned tactics are still typically helpful for a corporation. The aerospace and automobile sectors have been major drivers of CFD development. Modern race vehicles contain aerodynamic additions that have been developed throughout time to take the fluidic advantage into account and enhance the dynamics and mobility of the vehicle. Other aerodynamic appendages, like as front and back wings, sidepod, and undertrays, can be useful in this situation.

The study is aimed in optimizing the aerodynamic performance of a race car wing; therefore, the wing models and characteristics are changed from that of a conventional wing setup. Anderson, provided in-depth theoretical knowledge for the Computational Fluid Dynamic (CFD) studies [1]. Belega et al. presented the simulation approach for Nose Cone and other aerodynamic attachments [2]. Kirshan Chawala found that aerodynamic attachments are often made of super light materials like structural foam, Polyurethane (PU) foam [3]. Dahlberg et. al presented a real-life application with a continuous composite monocoque chassis with various aerodynamic attachments [4]. Groover et al. facilitated as a modern source of information for the polymer foam processing and forming [5]. Karna et.all found that Taguchi as a time-saving optimization technique [6]. Freddi et al. focused on effect of different parameters using Taguchi optimization technique [7].

Khanzode et al. observed that Taguchi optimization provides a simple DOE approach as compared to other optimization techniques like metaheuristic algorithms, genetic algorithms, response surface etc. Also, Taguchi optimization approach is robust, and no prior formulation is required. It is used to maximize the acoustic performance of a double expansion chamber reactive muffler by optimizing certain dimensional parameters [8]. An optimized tactical blended-wing-body UAV platform obtained by the Taguchi Method is numerically analysed by Kapsalis et al. [9]. Wang et al. analysed the aerodynamic performance improvement of vertical axis wind turbines using Taguchi method [10].Steinfurth et.al. found that the enhancement of aerodynamic performance of a Formula student race car by means of active flow control [11]. Soyak et al. provided insight into aircraft wind design at low speeds using Taguchi method [12].

From above literature review, it is observed that the effect of wing flapping is overlooked. This paper focus on effect of wing flapping.

To find the design providing the maximizing the Lift-to-Drag ratio (C_L / C_D) and creating a set of 25. 3-D models for the same, in addition to the individual CFDs done in order to calculate the ideal parameters, would be a very resource-consuming effort. The aforementioned studies demonstrate how DOE techniques like Taguchi are used for the design and optimization of aerofoil structures across a range of applications. This study aims to demonstrate the usefulness of DOE methods for racing car aerodynamic body parametric optimization.

Aerofoil Structure

An aerofoil comprises the suction surface and the pressure surface, with the former associating itself with higher velocity and lower static pressure, while the latter has a higher static pressure. When the study is constricted to a cross-sectional level, i.e., a 2-dimensional view, the leading and the trailing edge are considered. However, in the case of a race car, the aerofoil is inverted to produce more down force in contrast to the ones observed in an aircraft to generate more lift.

The angle between the wing's chord line and motion direction is known as the angle of attack. The best aerodynamic form is an aerofoil because it generates a smooth airflow around it, with a little amount of turbulence periodically on its trailing edge as shown in Figure 1. Every aerodynamic item has a separation point, which is when the body's impact in generating laminar flow ceases and turbulence begins. With greater aerofoil surface facing directly into the wind, an increase in the angle of attack increases the frontal area of contact with the wing and the drag. In airplane aerodynamics, where a single-element wing is considered, maximum lift typically occurs when the angle of attack is around 15°, but this could be higher for specially designed Aerofoils. In the case of automobiles, inverted aerofoils are used to generate more negative lift (down force) by default.

Design of Wing Structure

Figure 2 shows standard front wing geometry divided into elements, which are assumed as a unique location which receives a different load at a specific aerodynamic condition. Figure 2 also depicts the assumption of three separate elements - 1, 2 and Center. Symmetrical elements are considered the same element. Although the element titled Center is identical to Element 1, it is considered a separate element due to it having a different geometrical neighborhood, and the additional influence of the nose cone right above it.

FIGURE 1 Nomenclature of an Aerofoil.

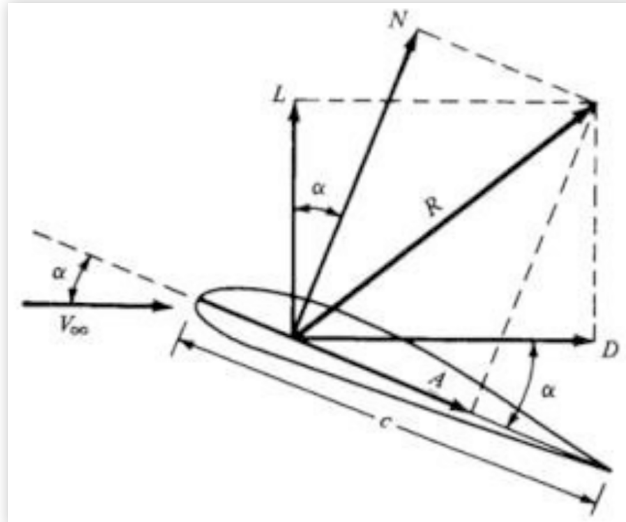
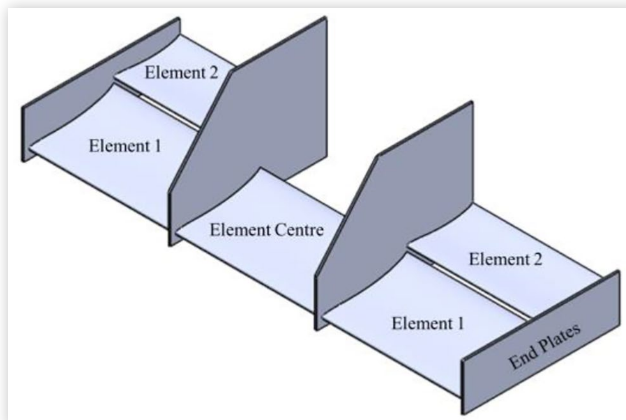


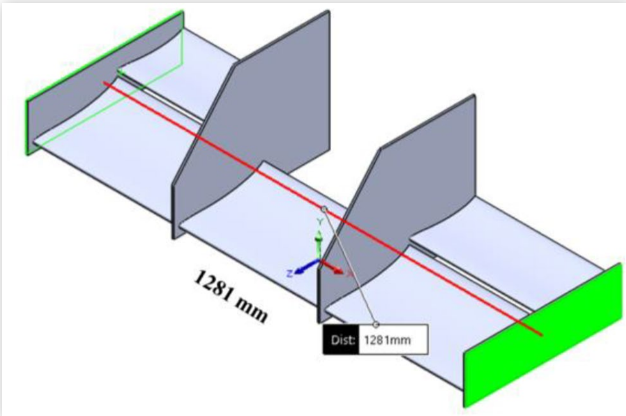
FIGURE 2 Geometry of a Front Wing.



Design of the wing setup is initiated with a two-dimensional cross-sectional geometry of the elements. The cross-section comprises a streamlined body generated by spline curves with its size scaled down with consequent elements. The entire cross-section is extruded to its supposed width to suit the vehicle application. The extrusion thickness is determined by considering the width of the vehicle to consider most of its frontal contact area into the aerodynamic range. In open-wheel vehicles, the width of the wings is a few millimeters less than the track width of the vehicle. Figure 3 shows the pictorial representation of the width of the Front Wing.

Real-world manufacturing is feasible by using super light materials like structural foams, which provide a

FIGURE 3 Dimension of a Front Wing.



considerable strength-to-weight ratio to withstand the down force and drag on the upper surfaces of the wing elements. The end plates are manufactured with any feasible engineering material, preferably sheet metal.

The airflow regime and airflow velocity affect the amount of drag. The drag affects the aerodynamic force. The CFD simulations are used to find aerodynamic forces acting on a body.

CFD Analysis of Wing Structure

In this work, the solver ANSYS Fluent is utilized to resolve all equations involving the conservation of mass and momentum. In flows requiring heat transfer or compressibility, an additional equation for energy conservation is established. The equation for mass conservation, also known as the continuity equation, is as follows:

$$\frac{\delta \rho}{\delta t} + \nabla\left(\rho \vec{v}\right) = S_m \tag{1}$$

Equation (1) is the general form of the mass conservation equation, which holds true for both incompressible and compressible flows. The source S_m is used to indicate the mass that was transferred to the continuous phase from the dispersed second phase, such as when liquid droplets vaporized (however, it is ignored in this study as the fluid environment is dry air). The conservation of momentum is described by Equation (2)

$$\frac{\partial}{\partial x}\left(\rho \vec{v}\right) + \nabla.\left(\rho \vec{v}.\vec{v}\right) = -\nabla p + \rho \vec{g} + \vec{F} \tag{2}$$

Where, p, $\vec{g}$, $\vec{F}$ is the static pressure, gravitational body force and external body force respectively.

The original 'conventional' cross-section sample is surrounded to simulate an air enclosure for CFD studies. The enclosure is long enough to have its rear edge near the front tires of the open-wheel vehicle, while the top edge covers the Nose Cone of the vehicle.

The CFD analysis is carried out on 2D cross-section of the aero foil. The front and the back extended parts of the domain are taken to visualize the airflow pattern after air leaves the aero foil.

Meshing

The domain is meshed using 2 dimensional Quad4 elements. The domain is first split into 3 parts. An element size of 10mm is used for 1 and 2, while 3 being sensitive for the analysis a smaller size of 5 mm is used for it. To account for the boundary layer an inflation is used on the aero foil edges with maximum thickness of inflation layer of 5 mm, 5 layers and a growth rate of 1.2.

Setup

A SST k-omega turbulence model is used for the analysis. The SST k-omega model is a robust model which can be used for number of cases.

The inputs are run to the constant velocity of 80km/h or 22.22 m/s, with the standard gravity of - 9.8107 m/s^2 along the Z-coordinate, with SIMPLE algorithm for computation with hybrid initialization of 20 iterations. The lift and drag coefficients are added to be calculated during the simulation run as well.

In order to optimize geometry, a maximizing or minimizing parameter should be laid out. An aerodynamic attachment which aims at maximizing the lift must also have its drag component taken into consideration, especially for a multi-element setup, as the frontal resistances may vary due to geometrical variances. Hence a C_L / C_D ratio is taken as a maximizing parameter for optimization. The maximizing of this ratio aims to have a higher value of C_L with a considerably lower value of the C_D.

Taguchi Analysis for Parameter Optimization

Theory

Genichi Taguchi, a Japanese engineer and statistician, created the Taguchi Analysis quality control approach, which stresses the roles of research and development and product design and development in lowering the incidence of flaws and failures in produced items. To reduce variations and output, this strategy places a higher priority on product quality than on the manufacturing procedures. The Taguchi optimization was chosen above other optimization methods because our models are design prototypes. A method that allows a user to decrease sampling was needed, and the optimization process required dimensional adjustment.

There are three approaches to Taguchi Optimization-

1. Smaller-The-Better
2. Larger-The-Better
3. Nominal-The-Best

Our aim for the entire Aerofoil optimization is to find the optimum C_L/C_D ratio, which means having a decent higher C_L (lift coefficient) to improve vehicle lift, but also, to have a lower C_D.

The 'Larger-The-Better' algorithm is employed to optimize the C_L & C_D parameters.

Aerofoil Sample Setup and Parameterization

As shown in Figure 2, Element 1 and Element 2 are used as the load- bearing element for the wing and element three are used for maintaining the streamlined flow. Element 1 and Element 2 are affected by three parameters – the angle of attack of both elements and the vertical distance between the two elements.

FIGURE 4 Parameter Representation for Taguchi Optimization.

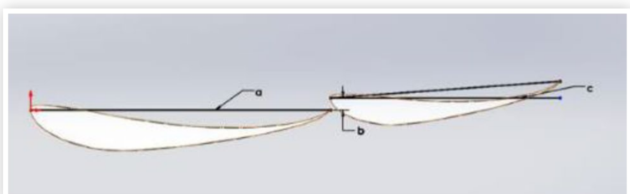


Figure 4 shows three crucial parameters used for Taguchi analysis. The three parameters are described below.

a. Angle of attack for Primary Aerofoil Element
b. Distance between Tail-End of Primary Aerofoil and Lift-End of Secondary Aerofoil
c. Angle of attack for Secondary Aerofoil Element.

Table 1 shows a set of values considered for optimization.

To justify the set of values considered for the study, the primary angle of attack should be near zero to collect most of the air from the bottom. The secondary element, however, should have a larger value of the angle of attack so that it can initiate lift from the horizontal component of the wing. The vertical distance between the wing elements will determine the short passage of air letting through the wings to avoid creating a major pressure difference.

TABLE 1 Set of Values Considered for Optimization.

Maximizing Factor – C_L/C_D Ratio			
Level	**a (°)**	**b (mm)**	**c (°)**
1	0	10	5
2	2.5	15	7.5
3	5	20	10
4	7.5	25	12.5
5	10	30	15

Orthogonal L25 Table for Taguchi Analysis

Normal optimization and parameter selection would lead to making 125 combinations of the following data sets, then conducting a CFD study on all the samples and finding out the C_L / C_D ratio for the same. Optimizing by Taguchi Method will reduce the workload by almost 80%, as it enables to the creation of only 25 combinations and then conducting the study on it to identify the best set of parameters in it.

Since there are five levels of data to be optimized, the L25 Orthogonal table is used to create samples. Table 2 explains the parameter setup for the same.

The Taguchi optimization is performed using Minitab software. Figure 5 shows Signal-to-Noise for three Parameters using Taguchi Optimization Technique.

From figure 6, it is observed that the optimized parameters generated are the angle of attack for primary aerofoil is zero degree, the distance is 15 mm, and the angle of attack for secondary aerofoil is 5 degrees. This geometry is used as the ideal front wing parameters for further CFD analysis. The figures 7, 8, shows the CFD analysis result of optimized wing structure.

The simulations of Wing structure generate graphs for Lift and drag coefficients. The figure 9 and figure 10 shows the Lift and Drag coefficient respectively obtained

TABLE 2 Set of L25 Orthogonal for Taguchi Analysis

Taguchi, P=3, L=5					Taguchi, P=3, L=5				
Run #	a	b	c	X	Run #	a	b	c	X
1	1	1	1	X_1	14	3	4	1	X_{14}
2	1	2	2	X_2	15	3	5	2	X_{15}
3	1	3	3	X_3	16	4	1	4	X_{16}
4	1	4	4	X_4	17	4	2	5	X_{17}
5	1	5	5	X_5	18	4	3	1	X_{18}
6	2	1	2	X_6	19	4	4	2	X_{19}
7	2	2	3	X_7	20	4	5	3	X_{20}
8	2	3	4	X_8	21	5	1	5	X_{21}
9	2	4	5	X_9	22	5	2	1	X_{22}
10	2	5	1	X_{10}	23	5	3	2	X_{23}
11	3	1	3	X_{11}	24	5	4	3	X_{24}
12	3	2	4	X_{12}	25	5	5	4	X_{25}
13	3	3	5	X_{13}					

a = Main Element Angle of Attack.

b = Dist. Between the Tail End of the Primary and the Lift End of the Secondary Aerofoil.

c = Secondary Element Angle of Attack.

P = Number of Parameters (3 - a, b, c).

L = Local Sample Size (5)

Using 25 sets of geometries with various combinations will yield various models ranging from X1 to X25.

All 25 of the samples from X1 to X25 were analyzed for a similar input velocity of 80 kmph. Table 3 shows the different values of CL, CD and *CL* / *CD* ratios obtained from the Samples generated for Taguchi Analysis.

TABLE 3 Values of C_L, C_D and C_L/C_D ratios.

Expt.	80 Kmph		
No.	C_L	C_D	C_L/C_D
X_1	491.628	20.0178	24.5598
X_2	504.0024	30.0168	16.79082
X_3	262.6206	37.5996	22.94213
X_4	917.2218	46.8834	19.56394
X_5	945.252	59.8836	15.78482
X_6	518.0148	28.2846	18.31429
X_7	713.7114	39.8154	17.92555
X_8	841.7208	52.0854	16.16045
X_9	974.6586	61.491	15.85049
X_{10}	479.3874	28.4364	16.85829
X_{11}	502.3134	38.6532	12.99545
X_{12}	712.0542	75.7428	12.33143
X_{13}	1119.87	53.6544	20.87183
X_{14}	574.2996	28.35	20.2576
X_{15}	487.1652	46.4466	10.48873
X_{16}	454.054	57.9	7.842079
X_{17}	603.434	74.2512	8.126922
X_{18}	366.217	42.5802	8.600578
X_{19}	523.97	51.096	10.25458
X_{20}	612.055	67.3878	9.082581
X_{21}	465.631	75.9048	6.134397
X_{22}	471.649	29.7576	15.84968
X_{23}	508.338	87.21	5.828876
X_{24}	371.534	64.8894	5.725628
X_{25}	296.393	52.2774	5.669693

FIGURE 5 Signal-to-Noise ratios for three parameters.

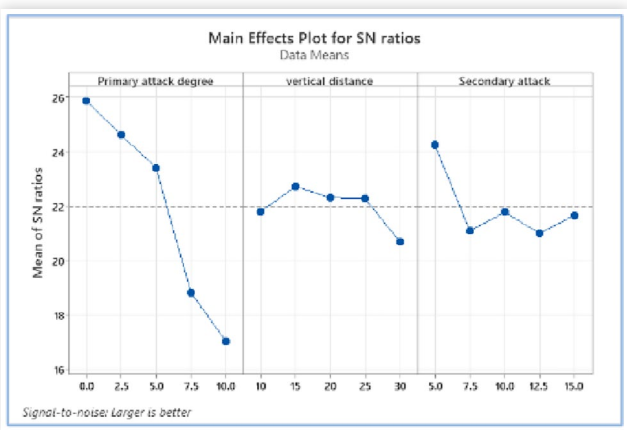


FIGURE 6 Cross Section Model of the Optimized Geometry

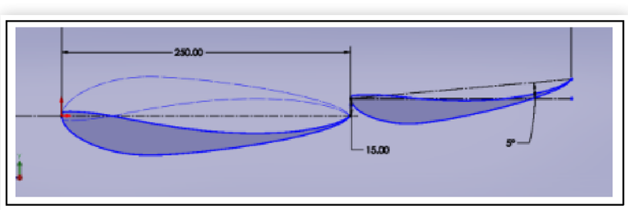


FIGURE 7 Aerodynamic Setup of the Optimized Geometry for CFD Simulation.

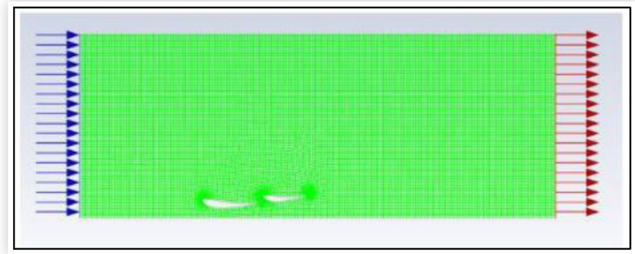


FIGURE 8 Velocity Streamlines generated by the Aerofoil at 80kmph Wind Velocity.

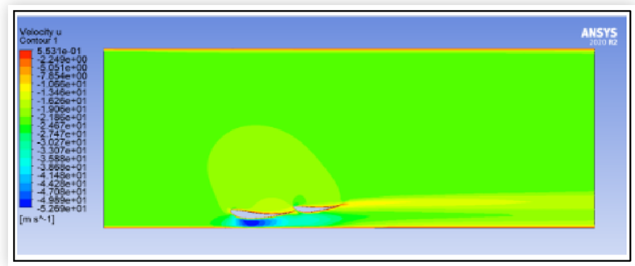


FIGURE 9 Lift Force Coefficient.

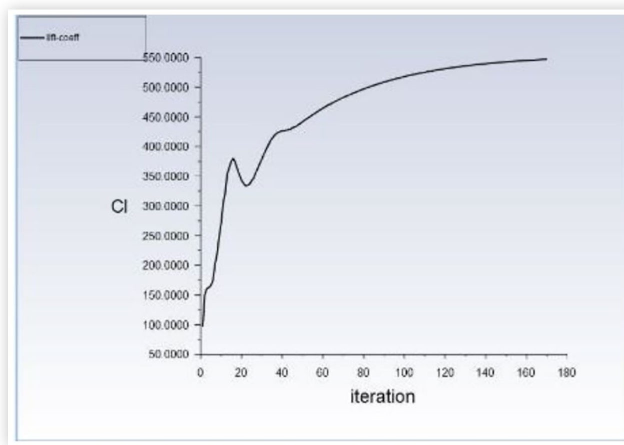
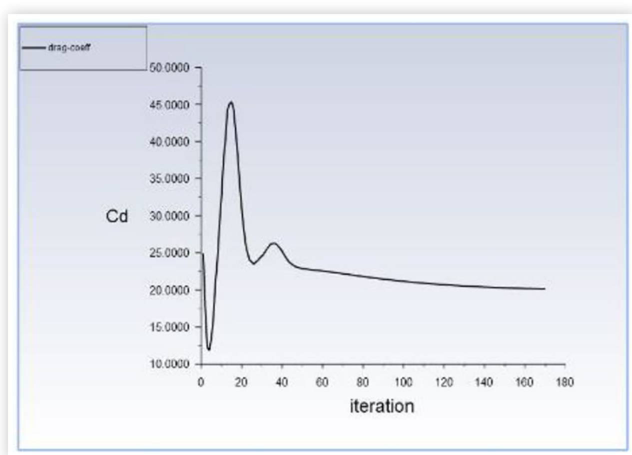


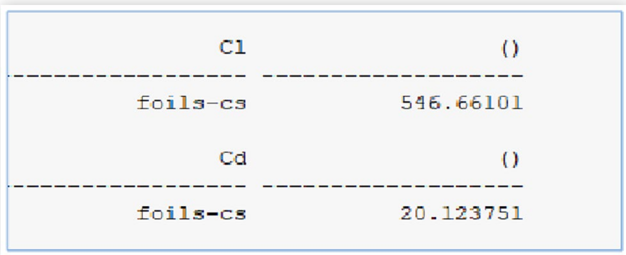
FIGURE 10 Drag Force Coefficient.



by CFD simulations. The figure 11 shows the values of C_L and C_D generated by ANSYS Fluent software.

Figure 12 shows the prototype of the wings for the same wing cross section. Figures 13 and 14 depict the primary and secondary element prototypes, respectively.

FIGURE 11 C_L and C_D values for optimized arrangement obtained from the Fluent script.



```
                 Cl                    ()
------------------ --------------------
           foils-cs             546.66101

                 Cd                    ()
------------------ --------------------
           foils-cs             20.123751
```

FIGURE 12 Prototype of the wings.

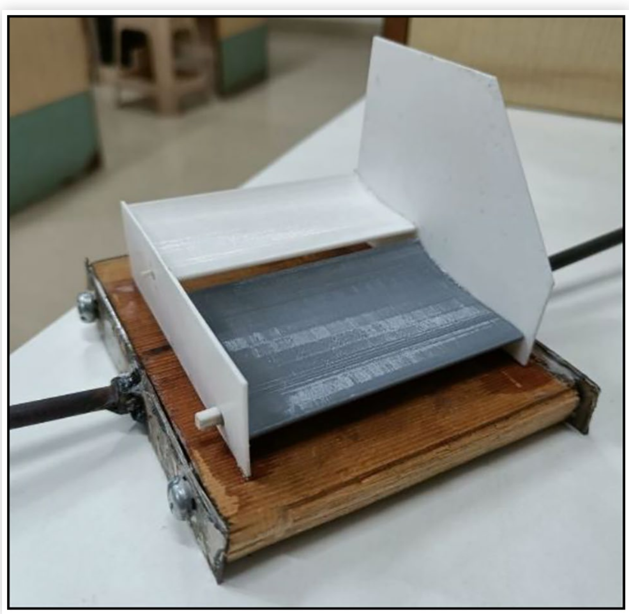


FIGURE 13 Primary Element.

FIGURE 14 Secondary Element.

Simulation of Wing Structure with Optimized Parameters

From the Taguchi Analysis result optimized wing structure with a primary angle of attack at 0 degrees, a distance between elements is 15mm and a secondary angle of attack at 5 degrees is used for CFD simulation.

From CFD simulation of the optimized wing, it is found that the C_L / C_D ratio is 27.16496, which is the highest value than the C_L / C_D ratio for 25 samples used in the Taguchi analysis. Hence, it can be concluded that the Taguchi optimized aerofoil will yield better results.

However, to further the credibility of the analysis, the test runs on the Aerofoil setup with the least optimized parameters is performed as well.

From the graphs obtained the least optimized parameters for the X_{25} setup are as follows.

$$a = 10^\circ,\ b = 30\ \text{mm},\ c = 12.5^\circ$$

The C_L / C_D ratio for X_{25} mentioned in Table 3 is 5.669693. The figure 15 shows geometry for X_{25} model.

The figure 16 shows the values of C_L and C_D for X_{25} model generated by ANSYS Fluent software.

FIGURE 15 Geometry for X_{25} model

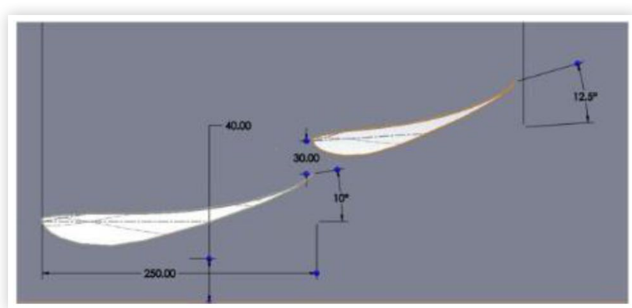
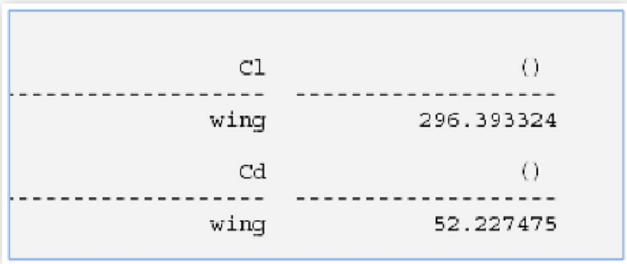
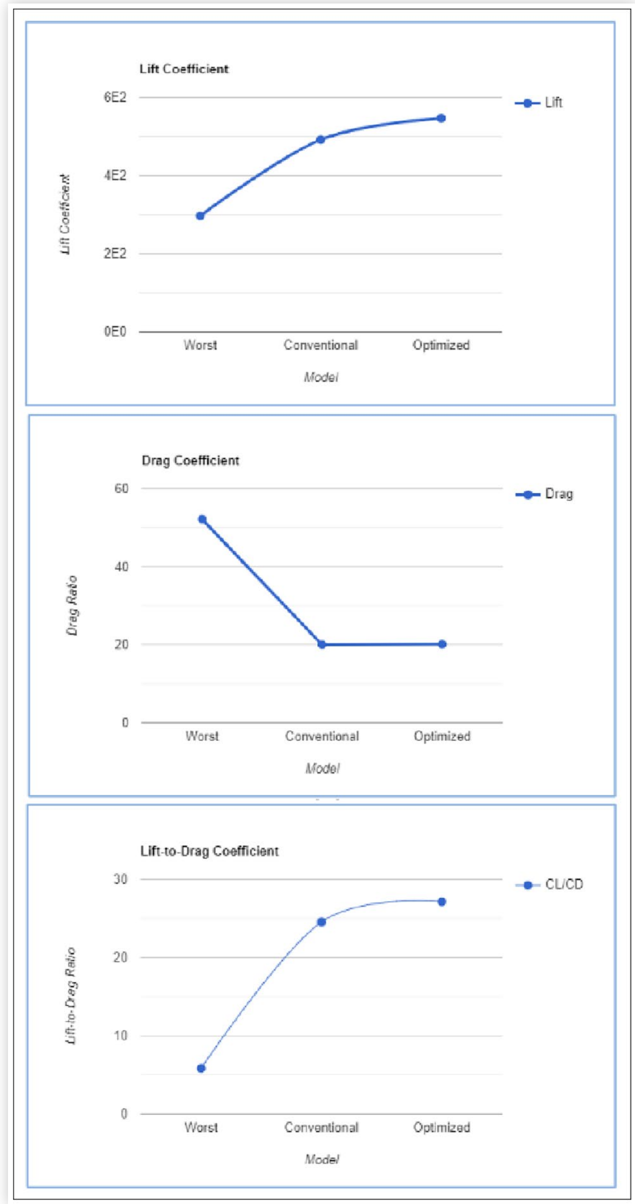


FIGURE 16 C_L and C_D values for nonoptimized X_{25} model obtained from the Fluent script.



```
                Cl                    ()
------------------  ------------------
              wing           296.393324
                Cd                    ()
------------------  ------------------
              wing            52.227475
```

FIGURE 17 Lift and Drag Comparison between the three models.



Result and Discussion

To understand the effect of an angle of attack on a lift and drag coefficient, 3 different models, viz. Optimized, non-optimized (worst) and conventional are compared. The figure17 (a), (b) and (c) of Lift, Drag and C_L/C_D ratio respectively shows comparison between 3 models

As it is imminent from the comparisons, the very high drag accounts for the poor performance of the worst-case model (X_{25} in this case). The conventional model, although it achieves a similar drag performance with respect to the optimized one, it lacks the lift improvement the latter provides. While the value of C_D remains variable to different design factors, adjusting the angle of attack can minimize the drag forces caused by reducing the frontal area of impact. 25 sets of setup designs are considered as a part of the Taguchi optimization study, where the maximum value of C_L / C_D (out of the 25 samples) is found to be 24.5598 for X_1 model, and the average is found to be 13.79242. With the CFD analysis method, the C_L / C_D ratio is maximized to 27.16496 using optimized parameters, providing a 10.6 % improvement over X_1 model. The figure 18 shows the wind tunnel set up used for experimental investigation.

The X_5 model's C_L/C_D ratio is found to be 15.78, which is closest to the average C_L/C_D value of 13.79. Therefore, the X_5 model is considered for experimental testing. The figure 19 shows the X_5 test sample's scaled down prototype model.

The air velocity of 4.4 m/s, air density of 1.293 kg/m^3, and area of 0.015765 m^2 are the input parameters for experimental testing. After the experimentation, a lift force(*Fl*) of 165.5 N and a Drag force (*Fd*) of 10.8 N are obtained.

$$Fl = C_L \times \rho \times \frac{1}{2} V^2 \tag{3}$$

$$Fd = \rho \times C_D \times A \times \frac{1}{2} V^2 \tag{4}$$

Where, ρ is the fluid density, V represents the object velocity, and A represents the projected frontal area.

FIGURE 18 Experimental Setup -Wind Tunnel

FIGURE 19 X_5 Test sample Prototype in the Wind Tunnel.

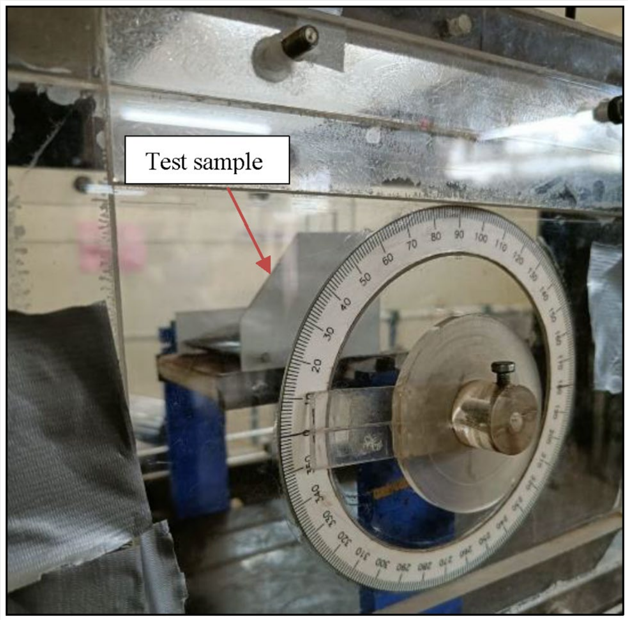


TABLE 4 Experiment Result Table

C_L	C_D	C_L/C_D
822.2214	53.6553	15.32407

By substituting the values of the lift force and drag force in Eq. (3) and Eq. (4), the C_L and C_D values are obtained. The table 4 shows the C_L and C_D values.

Conclusion

Wings are essential in optimizing the airflow, especially in eliminating the formation of pressure vortexes post-on-model flow regions. Wings are made of lightweight materials, including structural foams, honeycombs, etc. to avoid sagging due to self-weight as they are placed far from the actual chassis. Specific to the wing design, the wing should have a maximized C_L / C_D ratio. However, since Aerofoil profiles are usually similar spline curves, the changes in C_D values are very small and ultimately, produce very minute to no consequences. The only feasible alternative that remains is to improve the C_L values by optimizing design parameters such as angle of attack, a vertical air gap between wing elements, etc. Using Taguchi Analysis, it was concluded that the primary element, the element facing most of the air load, needs to have a very small angle of attack, almost parallel to the horizontal to collect the most of the air. The secondary element, however, must have a slightly more angle of attack to initiate the lift. The C_L/C_D ratio of X_5 model obtained by CFD analysis is 15.78 and by experimental testing is 15.32. It is observed that the C_L/C_D ratio for X_5 model obtained by Numerical analysis and Experimental investigation are well corroborated.

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Definitions/Abbreviations

C_L - Coefficient of Lift.

C_D - Coefficient of Drag.

CFD - Computational Fluid Dynamics.

p - Static Pressure.

$\vec{g}$ - Gravitational Body Force.
$\vec{F}$ - External Body Force.
$\boldsymbol{\rho}$ - Density.
t - Time.
$\vec{V}$ - Velocity
V - Velocity
Fl - Lift Force
Fd - Drag Force
A - Frontal area

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