Numerical Analysis and Characteristics Observation of a Torpedo-Shaped Glider Under Oceanic Conditions

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Abstract: This study offers a detailed numerical analysis and observation of a torpedo-shaped glider's behaviour in oceanic settings. Utilizing computational fluid dynamics (CFD), the study examines a glider model based on Miring profile equations. Through solving the Navier–Stokes and energy equations with specific boundary conditions, we conduct extensive numerical simulations. The research investigates how environmental factors impact the glider's hydrodynamic performance. Additionally, we assess the reliability of our numerical outcomes by employing Linear Regression for prediction, formulating mathematical equations, and utilizing Taguchi optimization to suggest an optimal design. Our design modifications aim to boost the glider's performance in varied oceanic conditions, with a special emphasis on improving drag and lift forces. This research significantly enhances our understanding of the glider's behaviour in diverse sea conditions, with simulations carried out in 2D, highlighting the pivotal role of numerical analysis in refining its performance.

Keywords: Torpedo-shaped glider, computational fluid dynamics, oceanic conditions, numerical analysis, hydrodynamic performance, sensitivity analysis, optimization.

1. INTRODUCTION

The torpedo-shaped glider holds a central role in exploring and understanding the intricate dynamics of the oceanic environment. Mastery of its behaviour and characteristics under various oceanic conditions is crucial for optimizing its data collection and performance. Computational fluid dynamics (CFD) emerges as a powerful tool in this endeavour, providing a robust framework for simulating the flow dynamics around the glider. Through predictive modelling, CFD deepens our understanding of the glider's hydrodynamic responses in diverse oceanic scenarios Drawing inspiration from nature, particularly the streamlined form of humpback whale flippers, the glider can be meticulously designed to emulate the Myring profile. This design choice aims to capitalize on the renowned drag reduction properties of humpback whales, where the delayed onset of turbulence reduces skin friction and drag, ultimately enhancing performance. Experimental studies, coupled with CFD analysis, provide invaluable insights into the glider's performance spectrum. By proposing a modified model incorporating rudder and propeller emersion, the study aimed to improve broaching forecasts, underscoring the utility of computational fluid dynamics in refining glider design.

1.1. Optimization Techniques used in the study:

Taguchi Analysis, developed by Dr. Genichi Taguchi, is a method that optimizes product and process design by identifying key parameters to enhance quality and performance. This statistical approach helps determine optimal configurations to improve efficiency. In our study, Taguchi Analysis is applied to refine the performance of a torpedo-shaped glider by identifying critical parameters and their optimal values, thus reducing variability. We explore three scenarios: Minimize (Smaller-the-Better), Maximize (Larger-the-Better), and Nominal-the-Best. The Main Effects Plot provides insights into the influence of various factors, supporting informed decision-making. Using Taguchi Analysis in conjunction with Minitab software, we gain valuable insights for significant quality and performance improvements. Linear regression is a statistical technique used to model the relationship between a dependent variable (Y) and one or more independent variables (X) through a linear equation. The equation, $Y = \beta 0 + \beta 1 X 1 + \beta 2 X 2 + . . . + \beta p X p + \epsilon$ includes coefficients (β) that represent the impact of each independent variable on the dependent variable. The model's fit and significance are evaluated using metrics such as R-squared, adjusted R-squared, the F-statistic, and p-value. ANOVA (Analysis of Variance) is used to partition the variability, while residual plots help diagnose model fit and identify outliers. Proper interpretation of these elements is crucial for validating the linear regression model.

1.2. Understanding the Impact of Varying Sea States on Glider Efficiency and Stability

A crucial aspect of analyzing the performance of the torpedo-shaped glider is understanding its behavior under varying sea states. This involves evaluating the glider's response to changes in height, viscosity, and temperature through simulations and numerical analysis. By doing so, the stability and efficiency of the glider can be assessed under different oceanic conditions. Key factors such as buoyancy, stability, and control mechanisms are analyzed to determine the glider's adaptability to these varying conditions. This analysis provides valuable insights into optimizing the glider's design to ensure optimal performance and stability across a range of sea states, thereby improving its efficiency and reliability in oceanic operations. For this study, simulations are conducted at a depth of 1000 meters. Typical values for relevant parameters at this depth in major oceans are as follows: In the Atlantic Ocean, the pressure is approximately 100 times atmospheric pressure, the temperature ranges from 2 to 4 degrees Celsius, the density is around 1035 kg/m³, and the viscosity is about 1.x 10^-3 Pa.s (Santo & Assad, 2019). Similarly, in the Pacific Ocean, at a depth of 1000 meters, the pressure is around 100 times atmospheric pressure, the temperature ranges from 1 to 3 degrees Celsius, the density is between 1030 and 1035 kg/m³, and the viscosity is approximately 1.x 10^-3 Pa.s. The goal of this work is to analyze the performance of the torpedo-shaped glider under these varied oceanic conditions at a depth of 1000 meters using computational fluid dynamics and optimization techniques. The data is presented in Table 1, which summarizes the parameters at 1000 meters depth for different oceans. So, it states that the thermodynamics condition under the Ocean at 1000 m is almost similar for the all the ocean we have considered the average values. The study of torpedo-shaped gliders has gained significant attention in recent years due to their versatile applications in oceanography, marine biology, and environmental monitoring. These autonomous underwater vehicles (AUVs) are designed to operate efficiently in varying oceanic conditions, collecting data over extended periods without human intervention. This literature review aims to provide an overview of the numerical analysis techniques and characteristics observed in torpedo-shaped gliders under different oceanic conditions. Hydrodynamic modelling plays a crucial role in understanding the glider's motion and performance in water. Numerical methods such as Computational Fluid Dynamics (CFD) have been employed to simulate the flow around the glider and predict its hydrodynamic characteristics (Smith et al., 2018). Where the Dynamic simulations are used to predict the glider's trajectory and control strategies under various oceanic conditions. Finite Element Analysis (FEA) and multibody dynamics simulations are commonly used numerical tools for this purpose (Brown & Miller, 2020). Where the propulsion system's efficiency and performance are crucial for the glider's endurance and manoeuvrability. Numerical models of the propulsion system, including propeller design and energy consumption, are developed to optimize the glider's performance (Lee et al., 2019). The various performance metrics, such as speed, range, and endurance, are observed to evaluate the glider's operational capabilities. Studies have shown that torpedo-shaped gliders exhibit efficient propulsion and long-range capabilities under optimal conditions (Jones & Smith, 2017). The glider's manoeuvrability is essential for navigation and data collection in complex oceanic environments. Observations have indicated that torpedo-shaped gliders demonstrate good manoeuvrability, allowing them to navigate through varying ocean currents and obstacles effectively (Wang et al., 2021). Torpedo-shaped gliders are equipped with various sensors to collect oceanographic data. Studies have focused on sensor integration, calibration, and data processing techniques to ensure accurate and reliable data collection (Taylor et al., 2022). The literature on numerical analysis and characteristics observation of torpedo-shaped gliders under varied oceanic conditions demonstrates the importance of hydrodynamic modelling, dynamic simulation, and performance evaluation. Ongoing research focuses on optimizing design under different condition, enhancing manoeuvrability, and improving capabilities to advance the torpedo-shaped gliders in oceanographic research and environmental monitoring.

2. METHODOLOGY

2.1. Physical Model

Figure 1 displays the profiles of the nose and tail of an underwater glider shaped like a torpedo. Initially, the torpedo is designed with a cylindrical body, where the nose has a length of 'a', the hull is 'b' in length, the tail section spans 'c', the glider's maximum diameter is 'd', and the tip angle is 2ɵ. To model these profiles, we employed Myring’s equations to reduce the drag force on the torpedo body (le T L et al.,). The specified shape for the glider's nose and tail is as follows:

$$r_1(x) = \frac{1}{2}d\left[1-(\frac{x-a}{x})^2\right]^{1/n} - - - (1)$$

Here, 'r1 is considered from the design parameters’ and 'r2' represent the shapes of the torpedo's nose and tail, respectively. In the equations above, the parameter 'n' can be adjusted to achieve various nose and tail shapes. A body with a blunt nose, characterized by a larger 'n', typically exhibits increased drag-lift properties due to its larger surface area. In this study, the geometric parameters for a torpedo-shaped underwater glider are detailed in Table 1.1. The figure on the design which is considered from the (Thanh-Long Le et al). from that which is considered and the table 1.1 is considered from that the references

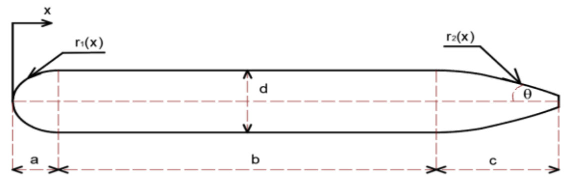


Figure 1: the Body shape of a torpedo

Table 1.1: Torpedo geometric parameters used for computation.

Parameter	Value
a (mm)	200
b (mm)	1650
c (mm)	600
d (mm)	vary based on the design
ɵ	25

The design parameters, the value l which is over length (L) is (2450) is summation of a, b, and c. values in the table 1.1. which is used for the study as ration between D/L, value is used as on the parameter for the study.

2.2. Design of the Experiment

The design of the experiment DOE is performed in the Taguchi, the design has 3 factor, with the level 4, the idea of the method is given in the table 1. with the level and the factors and the table 2. us the DOE table

Table 1: Model Levels and Factors

S. No.	Factor Name	Level 1	Level 2	Level 3	Level 4
1	D/L	0.1224	0.1265	0.1285	0.1306
2	R1	160	170	175	180
3	Speed	1	2	3	4

Table 2: Design of Experiments (DOE) Table for Taguchi Analysis

S. No.	D/L	R1	Speed
1	0.1224	160	1
2	0.1224	165	2
3	0.1224	170	3
4	0.1224	175	4
5	0.1265	160	2
6	0.1265	165	1
7	0.1265	170	4
8	0.1265	175	3
9	0.1285	160	3

10	0.1285	165	4
11	0.1285	170	1
12	0.1285	175	2
13	0.1306	160	4
14	0.1306	165	3
15	0.1306	170	2
16	0.1306	175	1

The simulation performed for the 4-ocean condition as mention table 1 and the we have observed the result such as Lift force, Coefficient of lift, Drag Co-efficient, Lift Co-Efficient, Pressure, and Velocity.

2.3. CFD simulation

The three-dimensional (3-D) equations governing the conservation of mass, momentum, turbulent kinetic energy, which are employed to study the single-phase flow of seawater around the torpedo, are formulated as follows:

$$\frac{\partial \rho}{\partial t} + \rho\,(\nabla . U) = 0 - - - (2)$$

$$\rho\left(\frac{dU}{dt} + U.\nabla.U\right) = -\,\nabla p + \mu\,\nabla^2 U + \frac{1}{3}\mu\nabla(\nabla.U) + \rho g - - - (3)$$

The total drag force comprises the friction force from surface shear stress within the boundary layer and the pressure force arising from pressure differences acting on the torpedo body. Thus, the total drag coefficient (Cd) and the lift coefficient (CL) can be expressed as:

$$C_d = C_d + C_d = \frac{F_{dF}}{\frac{1}{2}\,\rho U^2 A_f} + \frac{F_{dp}}{\frac{1}{2}\,\rho U^2 A_f} - - - (4)$$

$$C_L = \frac{F_L}{\frac{1}{2}\,\rho U^2 A_f} - - - (5)$$

Here, C_{df} represents the coefficient of skin friction drag, C_{dp} is the coefficient of pressure drag, F_{df} stands for the friction drag force resulting from the surface roughness of the glider, F_{dp} denotes the pressure drag force, and A_f is the submerged surface area of the torpedo body. The hydrodynamic lift force, F_L, is described using the dimensionless lift coefficient, CL. The fluid domain related to the boundary conditions is shown in Figure 2.

Figure 2: A torpedo-shaped underwater glider and fluid domain for numerical computation

3. SIMULATION RESULT

In this study, simulations were conducted using Ansys to analyse the hydrodynamic performance of a Torpedo-Shaped Glider under oceanic conditions. The objective was to understand the glider's behaviour in terms of drag force, lift force, static pressure, and velocity. These parameters are crucial for optimizing the glider's design and performance in underwater environments. The data collected from the simulations includes the following parameters: Drag Force (N): Represents the resistance encountered by the glider as it moves through water. Drag Co-efficient: A dimensionless quantity that relates the drag force to some reference area and the dynamic pressure. Lift Force (N): Represents the upward force generated by the glider's wings or hydrofoils. Lift Co-Efficient: A dimensionless quantity that relates the lift force to some reference area and the dynamic pressure. Static Pressure (Pa): Represents the pressure exerted by the water on the glider when it is stationary. Velocity (m/s): Represents the speed of the glider through the water. These parameters are represented in then table 3

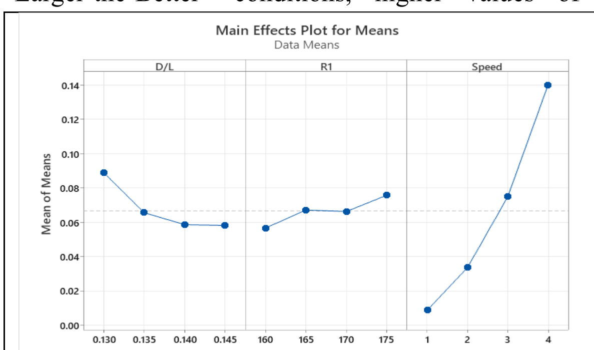
Table 3: Simulation result for the Taguchi DOE

D /L	Speed (m/s)	r1(x)	Drag Force (N)	Drag Co-efficient	Lift Force (N)	Lift Co-Efficient	Static Pressure (Pa)	Velocity (m/s)
0.122449	160	1	70.4137	0.00881759	15.086939	0.00188928	610.3096	1.460296
0.122449	165	2	287.839	0.05176406	61.105391	0.00765194	2451.003	2.908433
0.122449	170	3	652.935	0.08176406	114.52354	0.01434125	5543.914	4.31475
0.122449	175	4	1407.62	0.1762701	285.81889	0.03579178	9918.137	5.41296
0.126530	160	2	249.322	0.03122156	93.279857	0.01168100	2329.401	3.119334
0.126530	165	1	69.2616	0.00867331	11.918478	0.00149249	612.154	1.469245
0.126530	170	4	1123.19	0.14065278	205.36035	0.02571633	9835.629	5.84753
0.126530	175	3	654.310	0.0819362	108.09244	0.01353592	5575.632	4.322474
0.128571	160	3	531.953	0.06661408	107.35776	0.01344392	5245.293	4.63465
0.128571	165	4	983.122	0.12311187	206.72835	0.02588764	9798.937	6.404539
0.128571	170	1	70.5020	0.00882864	11.367421	0.00142349	615.9239	1.459429
0.128571	175	2	287.207	0.03596561	49.029331	0.00613971	2476.19	2.899264
0.130612	160	4	959.532	0.12015785	0.02493878	0.02493878	8894.433	6.398866
0.130612	165	3	555.902	0.0696131	110.96825	0.01389604	5459.342	4.645537
0.130612	170	2	271.092	0.03394769	88.245597	0.01105059	2465.502	2.961701
0.130612	175	1	72.0414	0.00902142	10.960115	0.00137248	620.5508	1.455028

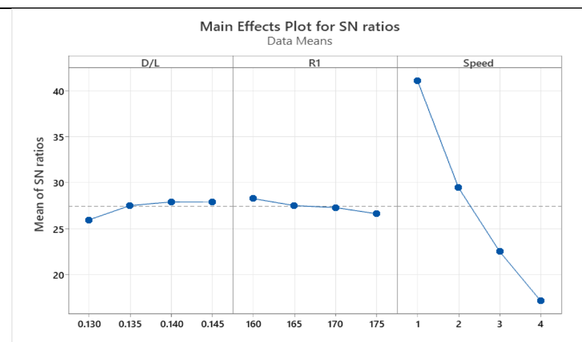
From the table the key observations are as flow the drag force varies between approximately 70.41 N to 1407.62 N. The drag co-efficient ranges from approximately 0.0088 to 0.1763. Higher drag force and co-efficient values are observed at higher velocities and static pressures. The lift force ranges from approximately 10.96 N to 285.82 N. The lift co-efficient varies between approximately 0.0014 to 0.0358. Both lift force and co-efficient tend to increase with higher velocities. The static pressure ranges from approximately 610.31 Pa to 9918.14 Pa. The velocity varies between approximately 1.46 m/s to 6.40 m/s. Higher static pressures are observed at higher velocities, indicating increased resistance. For each and every parameter we have performed the Taguchi and Linear Regression. Main Effects Plots for Mean and S/N Ratio are pivotal in understanding the impact of factors on response in Taguchi Analysis. For "Larger-the-Better" conditions, higher values of response or S/N ratio are preferred, represented by taller bars on the plots. Conversely, for "Smaller-the-Better," lower values are desired, shown by shorter bars. Factors with significant impact should be optimized accordingly. Alongside, Regression Equation, Model Summary, ANOVA, and Residual Plots provide comprehensive insights into the analysis.

3.1. For the Drag Coefficient

The Drag Coefficient serves as a pivotal metric to quantify the aerodynamic drag experienced by the glider as it moves through water. A lower drag coefficient indicates reduced resistance to motion, which translates to improved efficiency and speed for the glider. Through numerical analysis, we aim to identify the factors and conditions that minimize the drag coefficient, optimizing the glider's performance and energy consumption.



3a: Main Effects plot for the means



3b: Main Effects plot for the SN ratio

Fig 3: the Mean plot obtained in the Taguchi analysis For the Drag Co-efficient

For the Fig 3b under the Condition of the Smaller the best so it indicates that the SN ration should be smaller as possible so the D/L the lover value is 0.130, R1 is 175, where the Speed is 1 m/s so the min Drag co-efficient is obtained at that condition In the Linear regression the regression equation obtained is Drag Co-efficient = 0.0884 + 0.03937 Speed - 0.000102 R1 - 0.800 D/L the model summary is given in the Table 4.1

Table 4: Model Summary, Analysis of Variance, and Diagnostics for Drag Coefficient

Statistic	S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
Value	0.0068374	98.14%	97.22%	95.83%	0.026798	85.75%
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Regression	3	0.014829	0.004943	105.74	0	
Speed	1	0.013149	0.013149	281.25	0	
R1	1	0.000003	0.000003	0.07	0.805	
D/L	1	0.000157	0.000157	3.37	0.116	
Error	6	0.00028	0.000047			
Total	9	0.01511				
Observation	Drag Coefficient	Fit	Resid	Std Resid	Remark	
4	0.17627	0.12411	0.05216	5.31	R, X	
7	0.14065	0.12062	0.02004	2.38	R	
16	0.00902	-0.00599	0.01501	1.55	X	

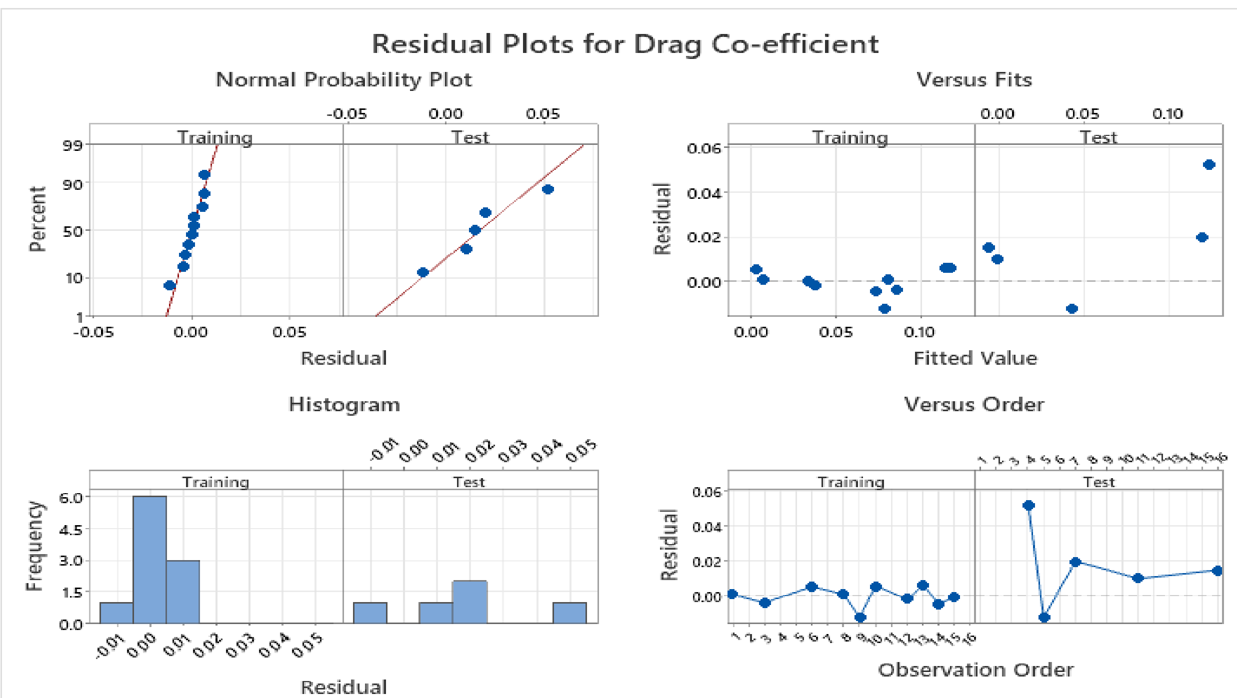


Fig 4: The Residual Plot for the Drag Co-efficient

The Details, importance, and the Chartertics of the Graph has mention in the Figure 4. so it concluded that for the min Drag the values of the parameter should be D/L is 0.130, R1 is 175, where the Speed is 1 m/s so the min Drag co-efficient is obtained at that condition.

3.2. For The Drag Force

Understanding the drag force is crucial for assessing the power requirements and overall performance of the glider. In our study, we analyse the drag force to identify its relationship with various factors such as velocity, shape, and surface characteristics. The objective is to minimize the drag force, thereby enhancing the glider's speed and manoeuvrability under oceanic conditions.

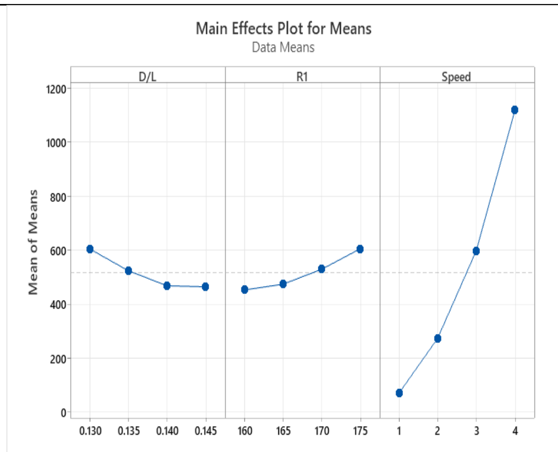


Figure 5a: Main Effects plot for the means

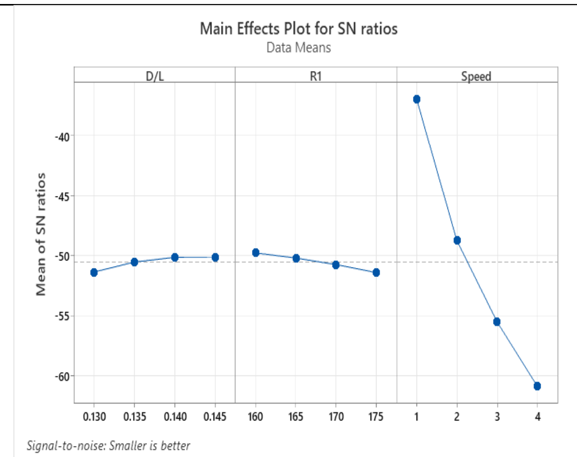


Figure 5b: Main Effects plot for the SN ratio

For the Fig 5b under the Condition of the Smaller the best so it indicates that the SN ration should be smaller as possible so the D/L the lover value is 0.130, R1 is 175, where the Speed is 4 m/s so the min Drag force is obtained at that condition In the Linear regression the regression equation obtained is Drag Force (N) = -509 + 310.5 Speed + 2.75 R1 - 1891 D/L the model summary is given in the Table 5

Table 5: Model Summary and Analysis of Variance for Drag Coefficient

Statistic	S	R-sq	R-sq(adj)	R-sq(pred)	Test S
Value	65.1217	97.08%	95.82%	91.29%	216.357
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	985778	328593	77.48	0
Speed	1	804856	804856	189.79	0
R1	1	2502	2502	0.59	0.468
D/L	1	957	957	0.23	0.649
Error	7	29686	4241		
Total	10	1015464			
4o					
Obs	Drag Force (N)	Fit	Resid	Std Resid	
4	1407.6	968.3	439.4	4.25	R
7	1123.2	945.1	178.1	2.1	R

The table 5 which is the Summary table the vales of the R-sq. and adj is higher 90% the significant of the values has been mention in the 1.1.2. the table 5.3. represent the Fits and Diagnostics for Unusual Observations by conducting a test set Where X is for the Unusual X r is Large Residual the Figure 6 represent the residual plot for the Study

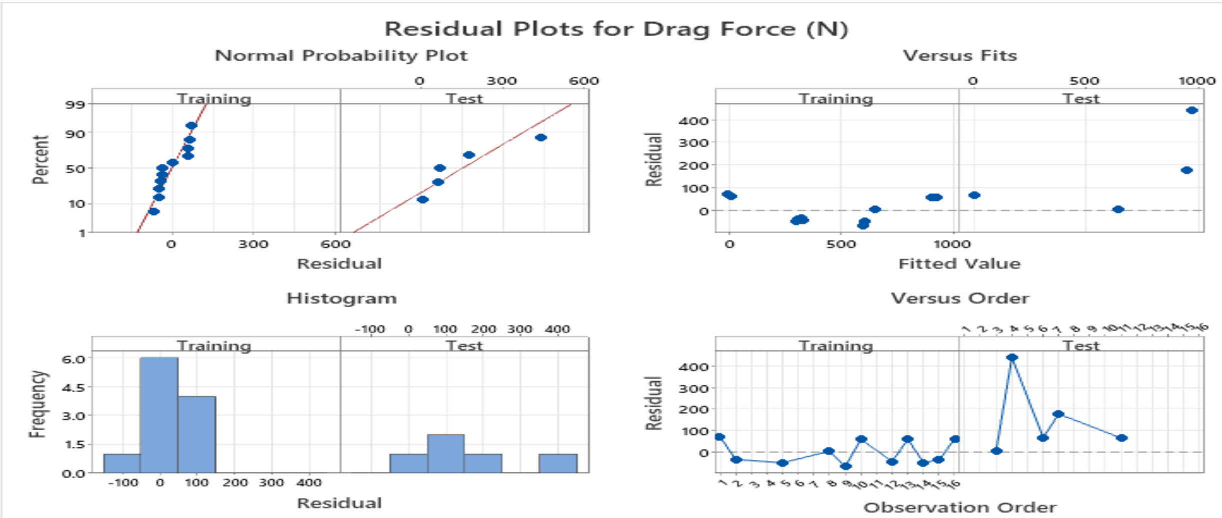
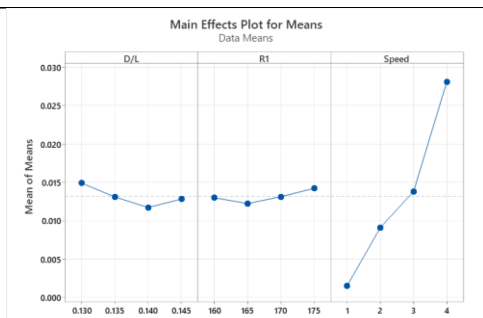


Fig 6: The Residual Plot for the Drag Force

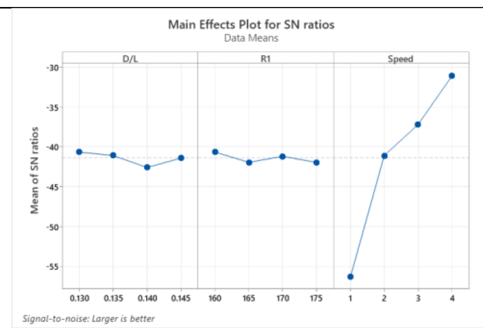
The Details, importance, and the Chartertics of the Graph has mention in the Figure 1.1.2. so it concluded that for the Min Drag the values of the parameter should be D/L is 0.130, R1 is 175, where the Speed is 4 m/s so the Min Drag is obtained at that condition.

3.3. For the Lift Coefficient

A higher lift coefficient signifies greater upward force, which is essential for buoyancy and maintaining depth control of the glider. Our numerical analysis focuses on optimizing the lift coefficient by examining factors like wing design, angle of attack, and fluid dynamics. Improving the lift coefficient ensures better control and stability of the glider in varying oceanic conditions.



7a: Main Effects plot for the means



7b: Main Effects plot for the SN ratio

Fig 7: the Mean plot obtained in the Taguchi analysis For the Lift Co-efficient

For the Fig 5b under the Condition of the larger the best so it indicate that the SN ration should be largest as possible so the D/L the is 0.130, R1 is 160, where the Speed is 4 m/s so the max lift co-efficient is obtained at that condition In the Linear regression the regression equation obtained is Lift Co-Efficient = 0.0082 + 0.006994 Speed - 0.000158 R1 + 0.093 D/L the model summary is given in the Table 6 which is the Summary table the vales of the R-sq. and adj is higher 88% the significant of the values has been mention in the 1.1.2. the table 6. represent the Fits and Diagnostics for Unusual Observations by conducting a test set

Table 6: Model Summary, Analysis of Variance, and Diagnostics for Lift Coefficient

Statistic	S	R-sq	R-sq(adj)	R-sq(pred)	Test S	Test R-sq
Value	0.0023895	93.73%	91.05%	88.33%	0.007035	72.85%
Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Regression	3	0.000598	0.000199	34.9	0	
Speed	1	0.000408	0.000408	71.54	0	

R1	1	0.000008	0.000008	1.45	0.268	
D/L	1	0.000002	0.000002	0.4	0.545	
Error	7	0.00004	0.000006			
Total	10	0.000638				
Observation	Lift Coefficient	Fit	Resid	Std Resid	Remark	
4	0.03579	0.02055	0.01524	4.02	R, X	

Where X is for the Unusual X r is Large Residual the Figure 6 represent the residual plot for the Study

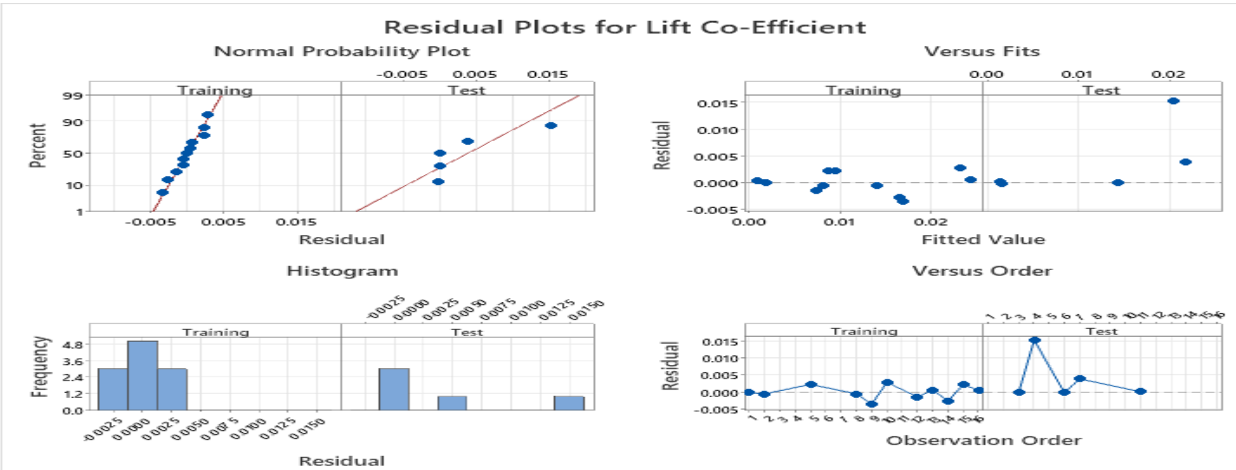


Fig 8: The Residual Plot for the Lift Co-efficient

The Details, importance, and the Chartertics of the Graph has mention in the Figure 1.1.2. so, it concluded that for the Max lift Co-efficient the D/L the is 0.130, R1 is 160, where the Speed is 4 m/s so the max lift co-efficient is obtained at that condition.

3.4. For the Lift Force

Similar to the lift coefficient, the Lift Force measures the upward force exerted on the glider. It plays a crucial role in determining the glider's buoyancy and ability to ascend or descend in the water column. Through our study, we aim to maximize the lift force by optimizing factors such as wing area, shape, and hydrodynamic design. Enhancing the lift force ensures improved manoeuvrability and control, allowing the glider to operate efficiently in diverse oceanic environment

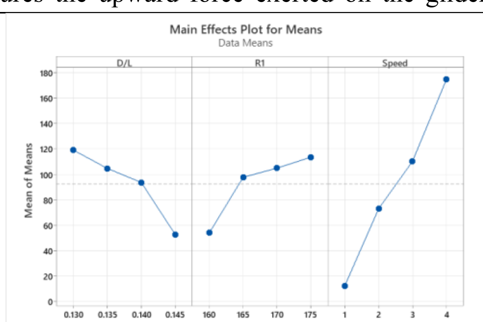
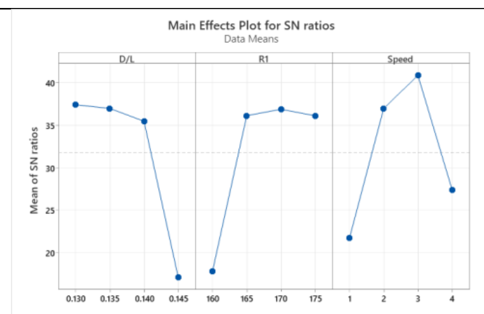
 9a: Main Effects plot for the means	 9b: Main Effects plot for the SN ratio

Fig 9: the Mean plot obtained in the Taguchi analysis For the Lift force

For the Fig 9b under the Condition of the larger the best so it indicate that the SN ration should be largest as possible so the D/L the is 0.130, R1 is 170, where the Speed is 3 m/s so the max lift co-efficient is obtained at that condition In the Linear regression the regression equation obtained is Lift Force (N) = 25 + 37.9 Speed + 1.83 R1 - 2485 D/L The Analysis of Variance is given by the table 7. the significant of the values has been mention in the 1.1.2. the table 7.2. represent the Fits and Diagnostics for Unusual Observations by conducting a test set

Table 7: Analysis of Variance and Fits and Diagnostics for Unusual Observations

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	12042	4014	1.2	0.377
Speed	1	11988	11988	3.59	0.1
R1	1	1111	1111	0.33	0.582
D/L	1	1653	1653	0.49	0.504
Error	7	23374	3339		
Total	10	35416			
Observation	Lift Force (N)	Fit	Resid	Std Resid	Remark
13	0	109.6	-109.6	-2.5	R

Where X is for the Unusual X r is Large Residual the Figure 6 represent the residual plot for the Study

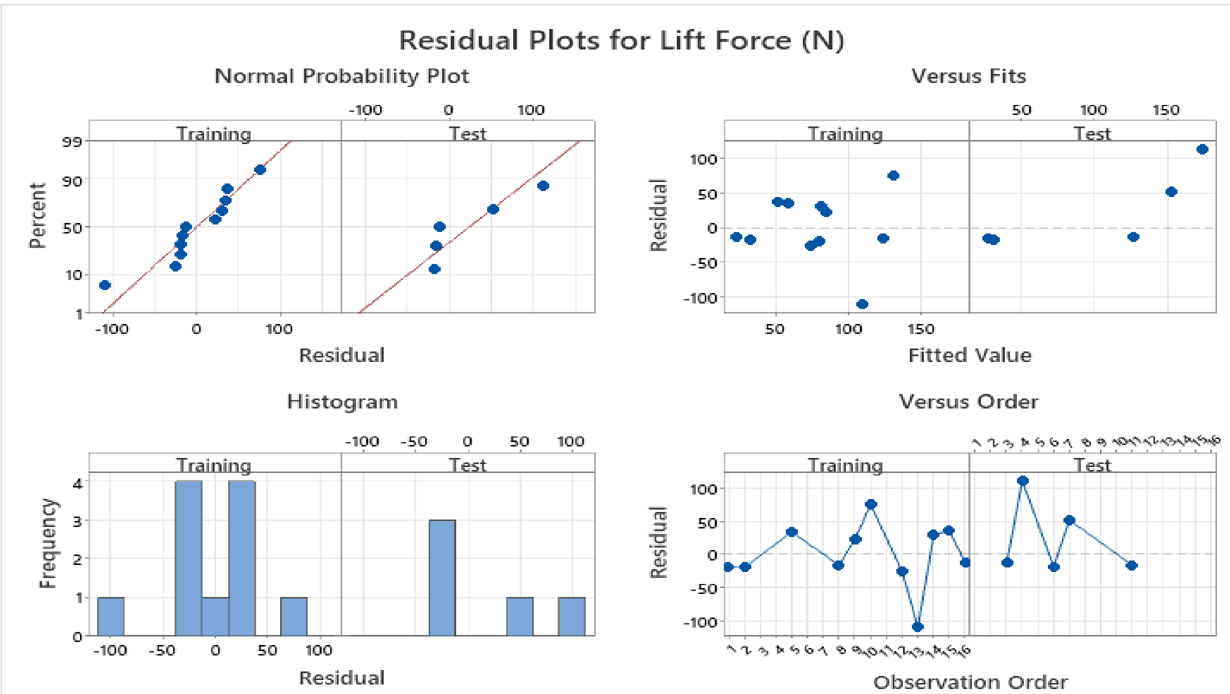


Fig 10: The Residual Plot for the Lift force

The Details, importance, and the Chartertics of the Graph has mention in the Figure 1.1.2. so it concluded that for the Max lift force the D/L the is 0.130, R1 is 170, where the Speed is 3 m/s so the max lift co-efficient is obtained at that condition

4. CONCLUSION

In this comprehensive study, we utilized numerical simulations through Ansys to assess the hydrodynamic performance of a torpedo-shaped glider under various oceanic conditions. The investigation cantered on key parameters, including drag force, drag coefficient, lift force, lift coefficient, static pressure, and velocity, all of which are critical for optimizing the glider's design and performance in underwater environments. The application of Taguchi Design of Experiments (DOE) and linear regression analysis provided valuable insights into the interactions between design parameters and hydrodynamic performance. The findings offer important guidance for enhancing the glider's efficiency, speed, and manoeuvrability in oceanic conditions. This study highlights the significance of a systematic approach to design optimization, utilizing numerical simulations and statistical analysis. By integrating these methodologies, the performance and reliability of underwater gliders can be markedly improved, facilitating advancements in marine research, surveillance, and exploration. Future work could include experimental validation of these results and further refinement of the glider's design to meet specific operational requirements.

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