

Modelling the effect of changing design fineness ratio of an airship on its aerodynamic lift and drag performance

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Abstract. In developing successful airship designs, it is important to fully understand the effect of the design on the performance of the airship. The aim of this research work is to establish the trend for effects of design fineness ratio of an airship towards its aerodynamic performance. An approximate computer-aided design (CAD) model of the Atlant-100 airship is constructed using CATIA software and it is applied in the computational fluid dynamics (CFD) simulation analysis using Star-CCM+ software. In total, 36 simulation runs are executed with different combinations of values for design fineness ratio, altitude and velocity. The obtained simulation results are analyzed using MINITAB to capture the effects relationship on lift and drag coefficients. Based on the results, it is concluded that the design fineness ratio does have a significant impact on the generated aerodynamic lift and drag forces on the airship.

1. Introduction

In recent years, airships have been anticipated to make its comeback into the mainstream commercial air transportation industry. Airships used to serve as the main air transportation means since the 1930s. However, due to a series of fatal incidents that hindered their design and development, particularly the infamous Hindenburg incident that marked the end of mainstream application of airships, jet aircraft effectively took over the role as primary means of passengers' air transport until today. Subsequently, the role of airships has been effectively delegated to only tourism and advertising purposes.

The current commercial transport jet aircraft has been facing few challenges lately. Among others, these include fluctuating fuel prices and increasing environmental awareness among the public that led to stricter operational rules by the aviation authority, which are causing problems for many airlines to maintain their profitable operation. Meanwhile, with the advancement in their design and technology, airships appear to have become a superior air transportation means than jet aircraft in few operational aspects. For instance, as indicated in Ref. [1], the environmental cost per seat kilometer of an airship is just about a quarter of that for jet aircraft. With the expectation that the future air transportation rules will be stricter with regards to environmental issues such as carbon emissions, this is a big advantage to use airship in commercial air transportation. Ref. [2] further compares operational characteristics of airship against other modes of transportation as tabulated in Table 1. The presented comparison result is taken to highlight that airship is very suitable to become an alternative means of public transport. An exemplary research that expresses this idea is the currently ongoing Multi-body Advanced Airship for Transportation (MAAT) project, which is supported by the European Union [3]. Another study related to having airships as public mass transport means has been reported in Ref. [4], which envisions it as



the potential solution for the increasing road traffic congestions. Overall, it can be summarized that the airships are cheaper to fly than helicopters and aircraft, able to carry high payloads and also operate in remote and hard-to-reach areas [5].

Table 1: Comparison of airships and other transportation modes [2]

Operational Characteristics	Airship versus Maritime	Airship versus Highway	Airship versus Railway	Airship versus Aerial
Speed	Much faster	Faster	Much faster	Much slower
Load Capacity	Less capacity	Much more capacity	Less capacity	Increased capacity
Load Adaptability	Much more flexible	Less flexible	Much more flexible	More flexible
Transportation Cost	Much more expensive	More expensive	Much more expensive	Much more economical

The increased suitability of airships for use as public air transport means can also be contributed to the revolutionary new designs that are much improved than conventional or traditional airship designs. Examples of the modern airship concept designs include Atlant, Aeroscraft, SkyShuttle and Airlander airships. Of particular interest in this study is Atlant-100 airship developed by Augur RosAeroSystems company, which is believed to be suitable option for mass public transport application. Computational fluid dynamics (CFD) simulation analysis on an approximate model of the Atlant-100 airship has been conducted in this study, where the model's design fineness ratio is varied to observe the impact of its generated aerodynamic lift and drag forces. Design fineness ratio is defined as the ratio of the airship's length to its width and it is an important parameter in designing the airship due to the expected impact on both its performance and transport capacity. Knowledge on its relationship with the performance of the airship helps in making better design decision in the trade-off between performance and capacity.

2. Lift and Drag Simulation Analysis

The approximate model of the Atlant-100 airship is constructed in CATIA software and it is illustrated in Figure 1. It should be noted that this model is developed based on the available design information within the public domain and may not accurately represent the actual airship design. Nevertheless, for this study, the constructed model is taken to be adequate since the primary focus of this study is on the effects of varying design fineness ratio on the airship's lift and drag forces. Total length of the model is 100 m while its width and height are 48 m and 35 m, respectively.

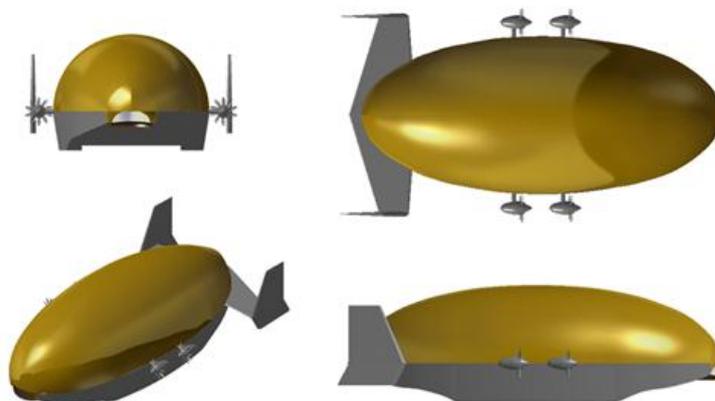


Figure 1: Constructed approximate computer-aided design (CAD) model of Atlant-100 airship

The CAD model is then used for CFD simulation analysis in Star CCM+ software. The turbulence model applied for the simulation is the Spalart-Allmaras (S-A) and polyhedral cell type is selected for the meshing. Both of these choices are made through the results of preliminary simulation studies that can be referred to in Ref. [6]. The model meshing details for the CFD simulation are tabulated in Table 2. To obtain good simulation data set for the trend analysis later, the setting for the simulation cases is made based on the full factorial design of experiment (DoE) method. In addition to the design fineness ratio, the velocity and altitude parameters in the simulation cases are also varied to represent the varying operational factors. In total, there are 36 different simulation runs executed for this study. Of important note, the variation of the design fineness ratio of the CAD model in this study is achieved by changing the airship's width while maintaining its length as constant. The CAD models corresponding to the three different design fineness ratios considered in this study are as illustrated in Figure 2, where the original design has the design fineness ratio of 2.08.

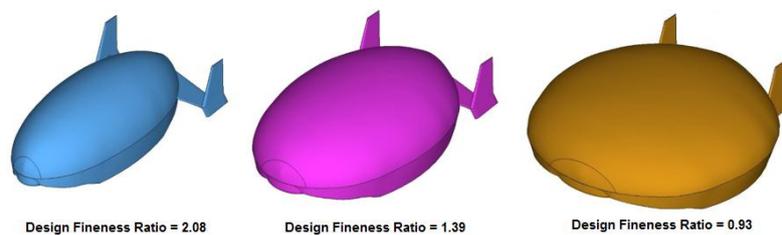


Figure 2: Different design fineness ratio models of the airship design

Examples of CFD simulation results from Star-CCM+ software for different design fineness ratios are depicted in Figure 3 to Figure 5. The velocity and pressure profile plots shown are for simulated flight at 1.5 km altitude with velocity of 100 km/h. The full simulation results are presented in Table 3.

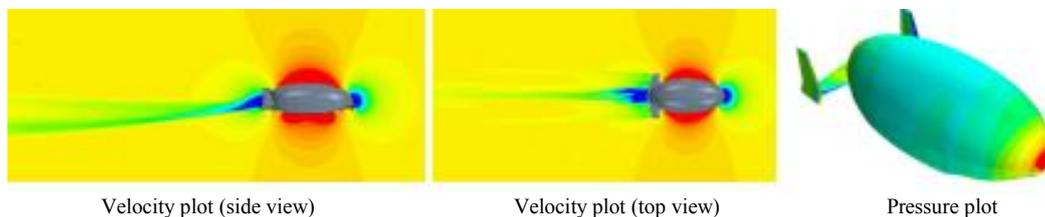


Figure 3: Results for design fineness ratio = 2.08, altitude = 1.5 km and velocity = 100 km/h

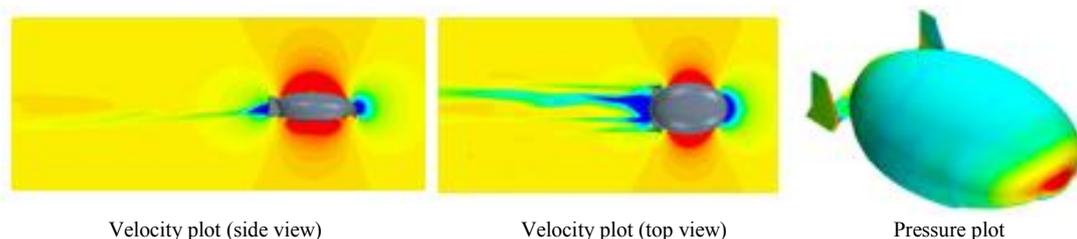


Figure 4: Results for design fineness ratio = 1.39, altitude = 1.5 km and velocity = 100 km/h

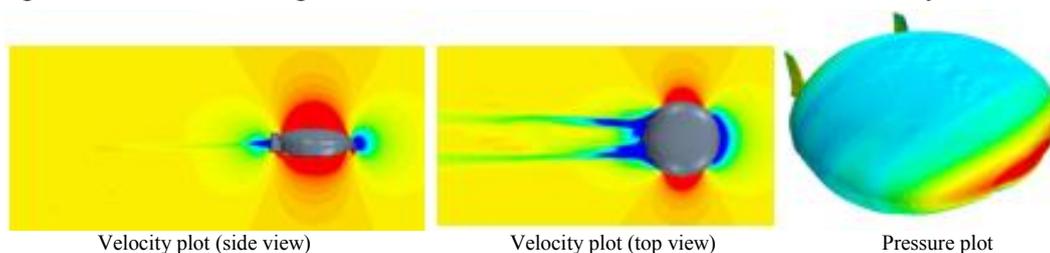


Figure 5: Results for design fineness ratio = 0.93, altitude = 1.5 km and velocity = 100 km/h

Table 2: Mesh details

Mesh Model	Polyhedral Mesher
Base size	3.2m
No. Prism Layer	12
Prism layer thickness	33.33% (Default)
Growth rate	1.3 (Default)
Y-values	All + y wall treatments (Default)
Surface Size (Target)	1.6m
Tunnel Surface Size	204.8m
No. of Cells	~ 6 millions

Table 3: Simulation analysis results from Star-CCM+

Run	Fineness Ratio	Altitude (m)	Velocity (km/h)	C _L	C _D
1	2.08	1500	100	0.026	0.024
2	2.08	1500	140	0.039	0.026
3	2.08	1500	190	0.039	0.027
4	2.08	1500	250	0.032	0.025
5	2.08	2000	100	0.029	0.026
6	2.08	2000	140	0.025	0.023
7	2.08	2000	190	0.031	0.026
8	2.08	2000	250	0.040	0.026
9	2.08	2500	100	0.040	0.027
10	2.08	2500	140	0.022	0.025
11	2.08	2500	190	0.017	0.023
12	2.08	2500	250	0.042	0.025
13	1.39	1500	100	0.048	0.036
14	1.39	1500	140	0.044	0.032
15	1.39	1500	190	0.047	0.033
16	1.39	1500	250	0.040	0.031
17	1.39	2000	100	0.038	0.036
18	1.39	2000	140	0.047	0.034
19	1.39	2000	190	0.055	0.034
20	1.39	2000	250	0.047	0.037
21	1.39	2500	100	0.052	0.036
22	1.39	2500	140	0.055	0.036
23	1.39	2500	190	0.054	0.036
24	1.39	2500	250	0.047	0.035
25	0.93	1500	100	0.055	0.033
26	0.93	1500	140	0.089	0.037
27	0.93	1500	190	0.069	0.033
28	0.93	1500	250	0.088	0.036
29	0.93	2000	100	0.061	0.033
30	0.93	2000	140	0.070	0.035
31	0.93	2000	190	0.060	0.032
32	0.93	2000	250	0.078	0.036
33	0.93	2500	100	0.059	0.032
34	0.93	2500	140	0.058	0.032
35	0.93	2500	190	0.072	0.035
36	0.93	2500	250	0.078	0.036

3. Modelling of the Effects Trend

The data obtained from the CFD simulation runs is then processed to model the possible relationship between the design fineness ratio and the generated lift and drag forces on the airship. For this study, the interest is on the difference in the generated aerodynamic forces when the design fineness ratio has been changed. With this in mind, the data in Table 3 can be rewritten as tabulated in Table 4, with the reference benchmark case settings as the original design fineness ratio of 2.08, altitude of 1500 m and velocity of 100 km/h. The processed data in Table 4 is then used as the input into MINITAB software for the statistical analysis and modeling.

Table 4: Data input into MINITAB for statistical analysis

Run	% Fineness Ratio Change	% Altitude Change	% Velocity Change	% C _L Change	% C _D Change
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	40.00	50.00	8.33
3	0.00	0.00	90.00	50.00	12.50
4	0.00	0.00	150.00	23.08	4.17
5	0.00	33.33	0.00	11.54	8.33
6	0.00	33.33	40.00	-3.85	-4.17
7	0.00	33.33	90.00	19.23	8.33
8	0.00	33.33	150.00	53.85	8.33
9	0.00	66.67	0.00	53.85	12.50
10	0.00	66.67	40.00	-15.38	4.17
11	0.00	66.67	90.00	-34.62	-4.17
12	0.00	66.67	150.00	61.54	4.17
13	-33.17	0.00	0.00	84.62	50.00
14	-33.17	0.00	40.00	69.23	33.33
15	-33.17	0.00	90.00	80.77	37.50
16	-33.17	0.00	150.00	53.85	29.17
17	-33.17	33.33	0.00	46.15	50.00
18	-33.17	33.33	40.00	80.77	41.67
19	-33.17	33.33	90.00	111.54	41.67
20	-33.17	33.33	150.00	80.77	54.17
21	-33.17	66.67	0.00	100.00	50.00
22	-33.17	66.67	40.00	111.54	50.00
23	-33.17	66.67	90.00	107.69	50.00
24	-33.17	66.67	150.00	80.77	45.83
25	-55.29	0.00	0.00	111.54	37.50
26	-55.29	0.00	40.00	242.31	54.17
27	-55.29	0.00	90.00	165.38	37.50
28	-55.29	0.00	150.00	238.46	50.00
29	-55.29	33.33	0.00	134.62	37.50
30	-55.29	33.33	40.00	169.23	45.83
31	-55.29	33.33	90.00	130.77	33.33
32	-55.29	33.33	150.00	200.00	50.00
33	-55.29	66.67	0.00	126.92	33.33
34	-55.29	66.67	40.00	123.08	33.33
35	-55.29	66.67	90.00	176.92	45.83
36	-55.29	66.67	150.00	200.00	50.00

The effect of changes in design fineness ratio, altitude and velocity parameters towards the lift and drag coefficients of the airship model can be observed from the main effects plot. Figure 6 shows the main effects plot for the generated aerodynamic lift coefficient. It can be observed that design fineness ratio has a significant effect on the aerodynamic lift generation since its plot has a very steep slope. In contrast, altitude changes have a rather negligible impact on the lift generation while velocity is fairly impactful. Meanwhile, Figure 7 is depicting the main effects plot for the aerodynamic drag coefficient. In similar fashion, impact from changing design fineness ratio can be observed to be very significant to the generation of aerodynamic drag in comparison to almost negligible impact both from altitude and velocity.

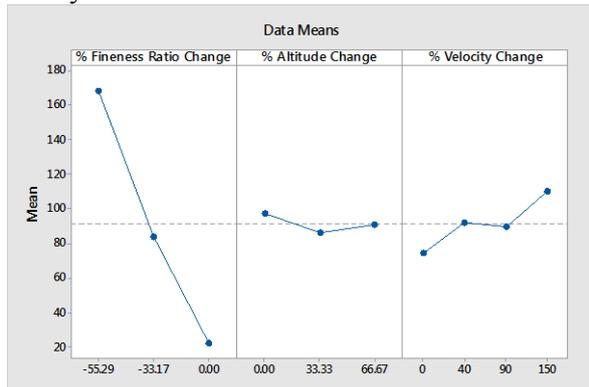


Figure 6: Main effects plot for % C_L change

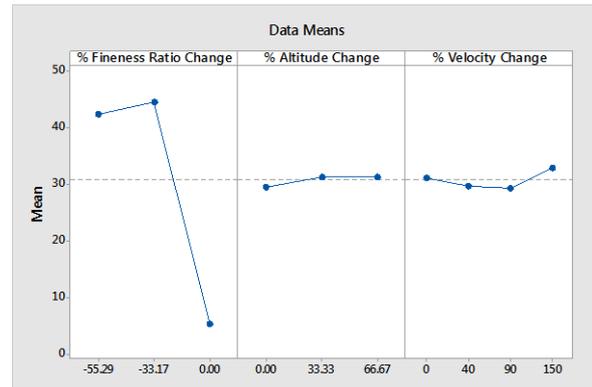


Figure 7: Main effects plot for % C_D change

In many cases, though the independent parameter itself may have a low impact, its interaction with other independent parameters can produce significant effect on the dependent parameter. Based on the interaction plots between design fineness ratio, altitude and velocity parameters in Figure 8 and Figure 9 for lift and drag, respectively, this situation is true. Looking at Figure 8, there is significant effect on aerodynamic lift from the interaction of design fineness ratio with velocity or altitude as indicated by the crossing of the plot lines. The same is observed for the generation of drag as shown in Figure 9.

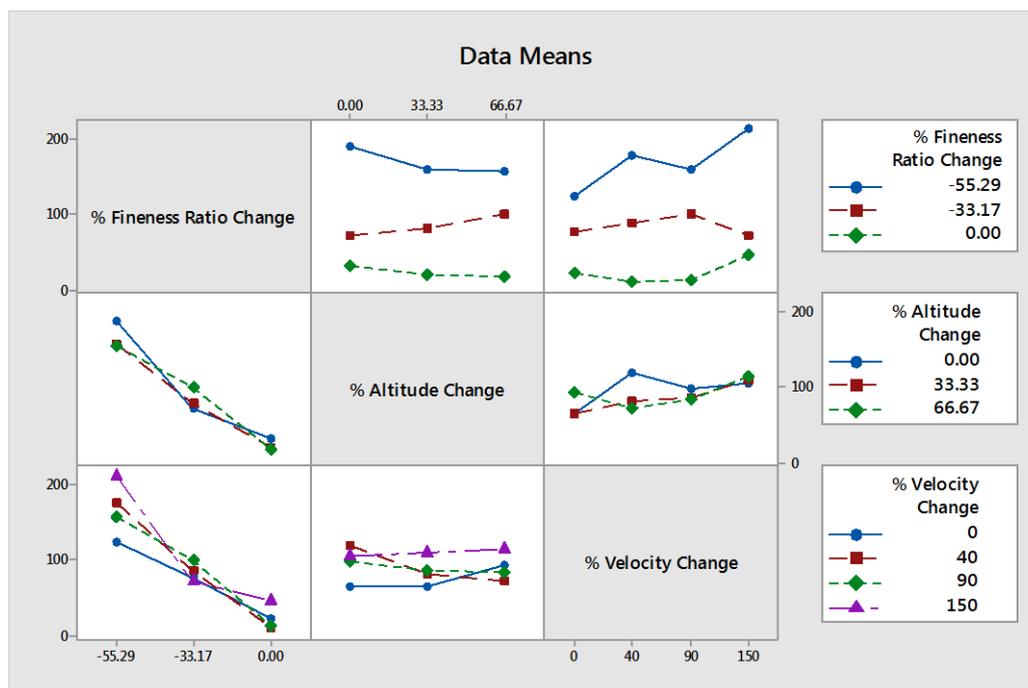


Figure 8: Interaction plot for % C_L change

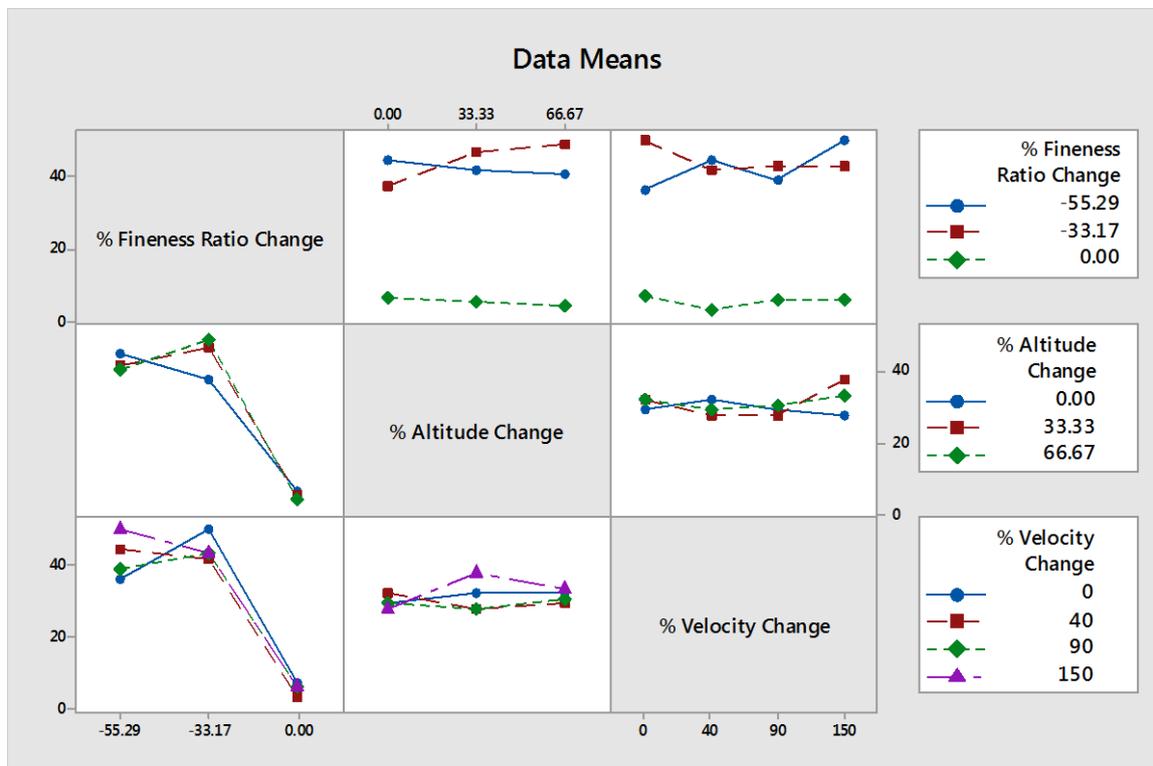


Figure 9: Interaction plot for % C_D change

Next, statistical regression model can be fitted to better capture the relationship between considered parameters and aerodynamic performance parameters of the airship design model. Using MINITAB, the fitted regression models for lift and drag forces are derived and they are indicated by Equation 1 and Equation 2, respectively, where VC is velocity change (in %), FRC is fineness ratio change (in %) and AC is altitude change (in %). Both fitted regression models have a high R-square value, which is used to measure how close the actual data are to the fitted regression line and how good the model is in capturing the variability of the response data around its mean. For Equation 1, its R-square value is 0.95, which means 95% of the effects relationship is adequately captured by the model. Meanwhile, the R-square value for Equation 2 is 0.97. Hence both of the fitted regression models can be taken to be adequately accurate in predicting the subsequent changes in the lift and drag forces on the airship design model when its design fineness ratio, altitude or velocity changes.

$$\begin{aligned} \% \text{ CL Change} = & 0.314 \text{ VC} + 0.04454 \text{ FRC}^2 - 0.0620 \text{ FRC*AC} - 0.01534 \text{ AC*VC} \\ & - 0.001201 \text{ FRC}^2*\text{AC} + 0.000396 \text{ FRC}^2*\text{VC} + 0.000128 \text{ FRC*VC}^2 \\ & + 0.000101 \text{ AC*VC}^2 \end{aligned} \tag{1}$$

$$\begin{aligned} \% \text{ CD Change} = & -2.036 \text{ FRC} + 0.0449 \text{ VC} - 0.02396 \text{ FRC}^2 - 0.01465 \text{ FRC*AC} \\ & + 0.00679 \text{ FRC*VC} - 0.000285 \text{ FRC}^2*\text{AC} + 0.000132 \text{ FRC}^2*\text{VC} \end{aligned} \tag{2}$$

All in all, based on the derived regression models, it can be concluded that the design fineness ratio has very significant impact on the generation of lift and drag forces for the airship design. The models in Equation 1 and Equation 2 can be used to predict the expected changes in aerodynamic lift and drag of the airship when the values of design fineness ratio is changed, along with the different operational setting of the velocity and altitude.

4. Conclusion

Aerodynamic performance characteristics of an airship are essential to determine its effectiveness and suitability in carrying out the intended mission. The aim of this study is to investigate the impact of the design fineness ratio on the generation of aerodynamic lift and drag forces on an airship. Based on the CFD simulation results and also the established regression models, it has been clearly highlighted that changing the design fineness ratio of an airship design can highly affect its aerodynamic performance, namely lift and drag forces acting on it during flight. The derived regression models have been shown to be of proper accuracy and can be easily used to predict the changes in lift and drag when the design fineness ratio, velocity and/or altitude parameters are changed.

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