Computational Estimation of Airship Aerodynamic Characteristics

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Abstract: The flight platform is lot of important where the airships are deemed to have wide range of applicability. Their various applications are like for long duration surveillance, high altitude radar platform, cargo transportation, etc. At high-altitudes, because of low density of air, airship needs to be designed and developed with huge body so as to obtain enough buoyancy for balancing its own weight. Thus, the aerodynamic parameters play important role in control and propulsion of airship. The study here investigates airship aerodynamics characteristics through numerical approach. Full-scale aerodynamics has been examined on sub-scale model. Three configurations like hull, hull-fin, and hull-fin-gondola are computationally analyzed for different angle of attack. Numerical results are found to be in good agreement with the experimental results with variation of 10.24% at ±15^0 angle of attack for hull configuration. On addition of appendages like fins to the bare hull, the increase in drag is 16.12%. For higher angle of attack, improved turbulence model need to be considered.

Keywords: Airship Aerodynamics, Computational Fluid Dynamics, Unstructured Mesh, CFDExpert Lite™

1. Introduction

Airships have an enormous potential as a platform for different purposes such as monitoring and surveillance, near space station keeping, telecommunication, military use, transportation of passengers and cargo and so on. Airship is expected to play an important role in construction of national economy. Airships also known as Lighter-than-air (LTA) are used to classify all the air displacement vehicles that obtain buoyancy due to the difference between weight of the inflation gas within their hulls and weight of the surrounding atmosphere which is displaced by their body. Airships differ from Aerostats such that they have their own propulsion system and are able to move from one position to other.

Airships are briefly classified based on its control and propulsion systems as traditional airships, heavy-lift weight airships, unconventional airships, non-rigid, rigid, and semi-rigid airships, hybrid airships, high altitude airships, and airships with buoyancy, etc.

2.1 Airships Potential

Airships have a wide range of performance capability that is available to be utilized along with its various applications. There is growing interest across the world in maximizing autonomous atmospheric flight vehicles as platforms operating for long period of time at very high range of altitude which from 18km to 100km. As the airplanes flies below 20km and space vehicles and spacecraft's above 100km, the space between these limits called near-space is remained unutilized. High altitude airships are best suited for such applications. The interest in these near-space solutions is increasing day-by-day, both in the commercial and military, because such solutions are less expensive and more flexible than space-based solutions. Moreover, these solutions offer the possibility of continuous coverage (persistence) over the ground target area. The near-space vehicle like high altitude airship has the ability to remain fix over target, but spacecraft or space satellites only passes over that location once each orbit. In some missions, the vehicle has to remain aloft for nearly one year.

Also, when compared to aircraft, airships generate lift from buoyancy instead of through aerodynamics by moving with very high speed. Consequently, they do not need to stay in motion to remain aloft. Therefore, they are able to stay over a specific location as well as move to a new location. In addition, airships also have the capacity to carry large volume, heavy payload. These characteristics make airship ideal for long-endurance surveillance missions. Also the congestion problems at highways, harbors and airports, and evidence of climate change have forced economically advanced nations to reconsider their transportation systems. Long-range aerial surveillance, communications relay, internet services relay, forest fire warning and laser weapon relay for missile defense are some of the other major areas where airship has lot of importance.

Even though research and development of airship lagged behind for a long time after the *Hindenburg* disaster, but the interest in airships has never been disappeared. Currently, interest in airships has been progressed by technological developments in a number of fields. Some of them are like, helium recovery, that is, use of inflammable helium instead of hydrogen in hull of airship. Composite materials science and metallurgy that provides with the availability of much lightweight materials. Computer assisted designing with use of high computation and simulation. Vectoring engines for powerful thrust in variable climatic conditions, satellite weather forecasting, fly-by-light avionics. However, now it is about to witness the return of airships as many of developed and developing countries have started to give a second hard look over the airship technology to utilize its unexploited potential.

2. Literature Review

The development of airships was lagged behind after the *Hindenburg* tragedy. That is after an accident of the most luxurious and mighty passenger transportation airship *Hindenburg*, which was remembered for years since it has caused fatal death of many passengers. But at the end of 20^{th} and dawn of 21^{th} century the research in airships again picked up to the progress due to technological advancements. Some of the researches and developments done and currently going-on, on airships across the globe are descripted here.

The experimental investigation of aerodynamics characteristics of the ZHIYUAN-1 airship was conducted by (Wang *et al*, 2010). It was done for the purpose of verifying some core technologies of stratospheric airship. The experiment was conducted in wind tunnel for studying part aerodynamics for design of control system and propulsion system. Also, the effects of appendages like fins and gondola over aerodynamic parameters were also investigated. It was found that drag almost gets doubled with flow variation from laminar to turbulent. The external gondola hardly contributed to the lift and stability but increased the drag very largely. Thus, it was suggested to install the gondola inside the hull of airship wherever possible.

(Beheshti *et al*, 2007, 2009) presented the aerodynamic drag and flow physics of high altitude airship configuration. They carried out the investigation experimentally in a water towing tank by down scaling the airship to small prototype model at Laboratory of Energy Conversion, Zurich. The purpose was to improve quantitative and qualitative understanding of aerodynamic characteristics. The effect of appendages, wind speed and crosswinds were investigated from measurements of force and moments. The experimental setup was validated by conducting the drag test on a sphere and comparing the results with standard results available from the literature. Then the experimentation for drag over hull and again over hull with fins and appendages were conducted. It was found that tailfins and payload gave 23% higher drag as compared to the ellipsoidal hull. Furthermore, the flow visualization with the help of colored and fluorescent dyes was conducted to improve the knowledge of aerodynamics of airship configuration. It gave an emphasis on the effects of, hull-appendage interference, transition and boundary layer separation.

The flow field surrounding the airship with propellers designed to blow on the basis of the Reynolds-averaged Navier-Stokes equations with SST turbulent models was calculated. Propellers were located at different positions around the airship surface directed to flow direction to separate vortexes off the body for reducing the drag force. (Fei and Zhengyin, 2009) modeled these propellers as an actuator disk instead of dynamic mesh overlap technique, because the main focus was on propeller generated flows and not the propeller itself. It was also found that the best position for propeller to blow was after leading sucking peak. Other than this position the friction drag coefficient was found to be increased. With stronger pressure jump and bigger diameter, the drag coefficient reduced was more.

The drag coefficient and the effect of fins and cars and over flat and streamline protuberances located at various positions along the hull were determined. For this purpose, two airship models were tested in NACA variable-density wind tunnel. One of the models was rounded off to produce blunter shape at its stern. (Abott, 1932) found that at higher values of Reynolds number the drag coefficient was affected very little by streamline protuberance. Also additional drag due to flat protuberance was less than the calculated drag of the protuberance alone. The total 20% of drag was increased due to fins and cars over the bare hull. Thus, it was concluded that no adverse interference effects would be expected due to change of shape of protuberance.

Technologies needed to build the renewable electrical power systems for long duration observation airship were investigated by (Colozza *et al*, 2005). Also, along with NASA'S Glenn Research Center, the initial investigations examined the management of power and distribution of architectures for a costal observing stratospheric concept. Various configurations of airships for various types of applications were identified. The uses of airships for long duration surveillance, airships as a stationary for high altitude radar platform were also studied in detail. High Altitude Airships (HAA) and High Altitude Aircrafts were compared in different aspect. It was concluded that airships had an advantage of long duration stay in the space, long endurance and high maneuverability over the aircraft. Also, various possible configuration and concepts of airships were put forth. A case study was carried out on the performance capabilities and power propulsion technology for a renewable, high altitude airship. It was shown that the power required for propulsion at East and West Coastal Cities of American continent at different latitude was different.

(Prentice *et al*, 2005) examined the airships for mode of transportation. They also have put forth the market need for airships that existed between air and marine transport due to its economic considerations. Comparison was done on the basis speed, freight rates, service and capability of transportation between aircrafts, airships, helicopters, rails and trucks. It showed that large airships were profitable offering rates above those typical for marine transport, but well below those of conventional air transport. Case study for long haul mission and short haul mission was conducted for airships between Hawaii and U.S. mainland, and from Canada to remote communities. It proved the importance of airships for mode of transportation.

3. Flow Modelling

Numerical methodology adopted throughout the entire work involves creation of geometry, preparation of computational mesh for Hull, Hull-Fin, Hull-Fin-Gondola configuration, imposing the boundary conditions, selection of appropriate turbulence model and solver setup like numerical scheme, order, coupling methods, convergence limit, etc.

3.1 CAD Rendition of Geometry

The scaled down model of actual ZHIYUAN-1 airship with scaling of 13.7 is framed in this section. Three configurations of geometries like Hull, Hull-Fin, and Hull-Fin-Gondola are modeled, but here only Hull is presented in detail. For this purpose any of the 3D modelling software is helpful. The software used is CATIA V5 R20 due to its simplicity and convenience in part designing, assembly, etc. All the complex parts are considered while dealing with original geometry. Figure 1 configuration.

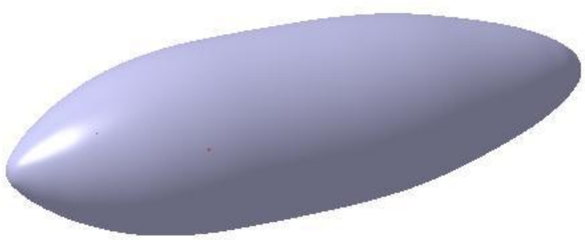


Fig.1 Airship Hull model without any appendages

The co-ordinates of geometry profile are imported into modeling tool using the technique of GSD PointSplineLoft from Excel. Geometrical dimensions of airship are reported by (Wang *et al*, 2010) where, volumetric Reynolds number is obtained using cube root of volume as the characteristics length.

3.2 Computational Mesh and Boundary Conditions

To carry out numerical simulations, the computational domain is extracted from solid model. Unstructured shell meshing is done using ANSYS ICEM CFD with mesh type as All Triangle. The mesh method used is patch independent for entire geometry. Meshing of the entire airship hull configuration is shown in Figure 2. As the flow physics is of more importance at aft part, to capture its effect, mesh refinement is required.

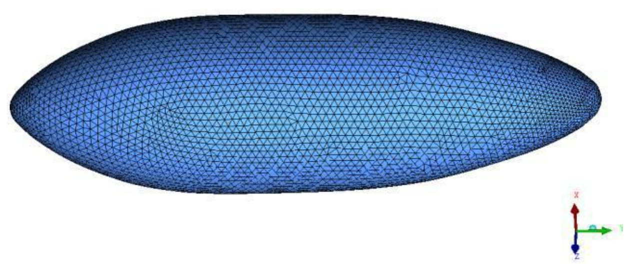


Fig.2 Unstructured meshing of Hull-configuration

Figure 2 also shows the clustering of mesh at the position where flow variations are supposed to occur. This refinement of mesh also helps in capturing the separated flows if any and the effect of wakes and vortices produced. Due to subsonic flow, larger size of cylindrical type computational domain is used and filled with tetrahedral elements as given in Figure 3.

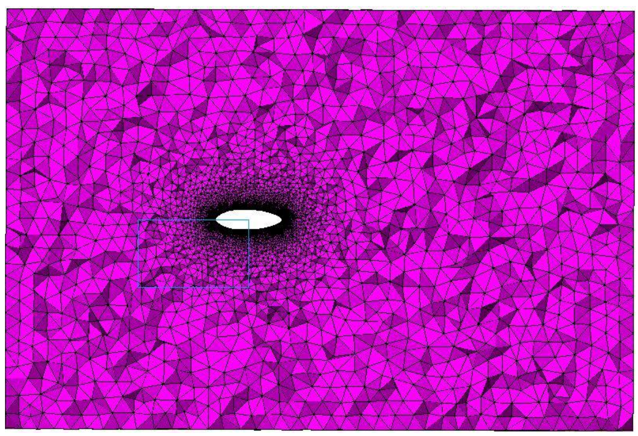


Fig.3 Computational domain with mesh

In order to capture the influence of boundary layer due to low Reynolds number flow, a prism layer with recommended value of y^+ as 1 is packed around the periphery of airship body as seen from Figure 4. This indicates that first cell near the surface is within the viscous sublayer of boundary layer. The inflation prism layer and tetrahedral elements are created by using

ANSYS Fluent/TGrid meshing mode tool. The computational mesh is made error free and has a quality within the acceptable limits for both shell and volume elements.

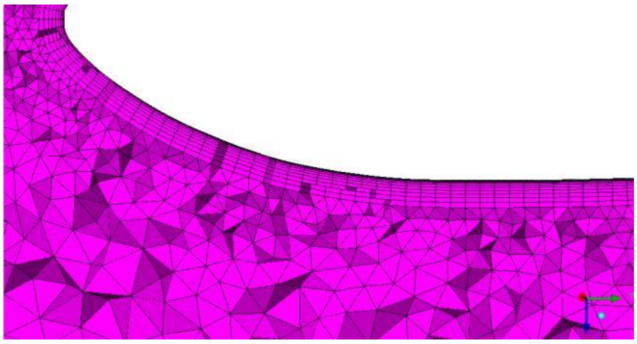
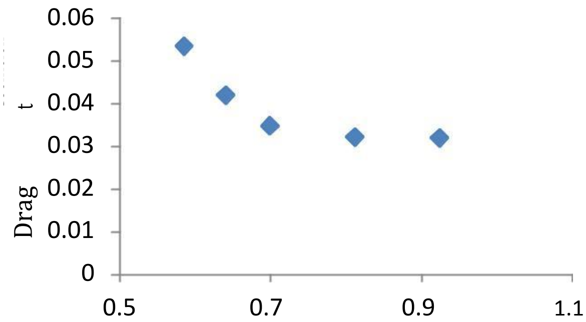


Fig.4 Prismatic layer mesh over the airship hull

Various mesh independence tests are performed to find the sufficient number of mesh elements for obtaining reliable results. These all tests are carried out on Hull configuration at specified free stream velocity and at zero angle of attack. Figure 5 shows the variation of drag coefficient with number of mesh elements. It is seen that a mesh containing approximately 0.8 million cells is fine enough to model our problem since there is no significant change in drag coefficient with further refinement of mesh.



Cell Count (N)x 10^6 in millions

Fig.5 Grid Independence Test

The domain of airship has inlet, outlet and farfield boundaries. Boundary condition of uniform free stream velocity is specified at upstream boundary and pressure outlet with atmospheric pressure is set at downstream boundary. Surface of airship is modeled as wall with no-slip boundary condition and the domain wall is imposed with farfield boundary condition. Flow inlet velocity is given as 60.39 m/s with volumetric Reynolds no of 2.58 x 10^6. To compute aerodynamic coefficients, the reference area of 0.4416 m^2 and reference volume of 0.2935 m^3 are used.

The computations are applied for following conditions:

- Airship hull configuration with angle of attack as 0^0, $\pm 9^0$, $\pm 15^0$, $\pm 21^0$, $\pm 30^0$.

All simulations are conducted via parallel computations (partition is done using METIS, a graph and mesh portioning tool) on 8-core processor for hull configuration. Simulations are conducted till the residues in continuity and momentum equations are dropped by four orders of magnitude (10^{-4}).

3.3 Governing Equations

The set of governing equations describing air flow surrounding the airship are Reynolds Averaged Navier-Stokes equations defined as follows:

Continuity:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

Momentum:

$$\frac{\partial}{\partial x_i}(\rho u_i u_k) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_k}{\partial x_i}\right) - \frac{\partial P}{\partial x_k} \quad (2)$$

Turbulence:

$$\frac{\partial}{\partial t}(\rho \tilde{v}) + \frac{\partial}{\partial x_i}(\rho \tilde{v} u_i) = G_v + \frac{1}{\sigma_{\tilde{v}}}\left[\frac{\partial}{\partial x_j}\left\{(\mu + \rho \tilde{v})\frac{\partial \tilde{v}}{\partial x_j}\right\} + C_{b2}\rho\left(\frac{\partial y}{\partial x}\right)^2\right] - Y_v + S_{\tilde{v}} \quad (3)$$

Where, ˜ is the transported variable identical to kinematic eddy viscosity. Second order upwind scheme is used to discretize the convective flux term in momentum equation and time integration is done with global time stepping. First order upwind scheme is used to discretize turbulence equation. AUSM (Advection Upstream Splitting Method) algorithm has been used for coupling Navier-Stokes equation. The kinematic eddy viscosity is modeled by using single transport equation Spalart-Allmaras Edward turbulence model due to its good performance in boundary layers with adverse pressure gradients. All the simulations are carried out within the framework of in-house developed Implicit RANS solver CFDExpert Lite^{TM} by the firm Zeus Numerix Pvt. Ltd. for unstructured mesh.

4. Results and Discussion

4.1 Computed Aerodynamic Drag

Aerodynamic drag over an airship hull configuration is obtained for different angles of attack. It is seen from Figure 6 that the computed coefficient of drag is in good agreement with experimental drag as measured by (Wang *et al*, 2010) for lower angle of attack within the range of ±15.

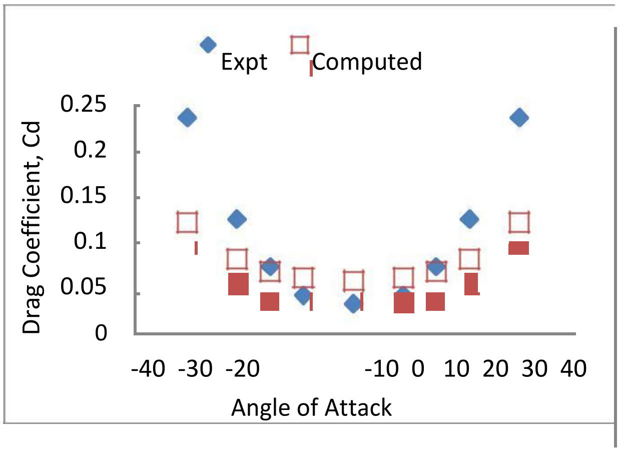


Fig.6 Variation of Drag coefficient with Angle of Attack

4.2 Computed Aerodynamic Lift

Aerodynamic lift is also obtained at different angle of attack for hull configuration. Figure 7 shows the variation of lift with angle of attack.

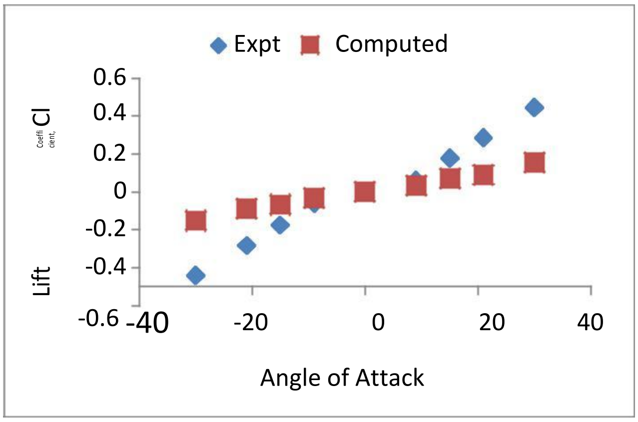


Fig.7 Variation of Lift coefficient with Angle of Attack

At $\pm 15^0$ angle of attack, the computed drag shows deviation of 10.24% when compared with experimental drag. For higher angle of attack these computational drag and lift are found less than the experimental one. This is because of the use of approximate one equation Spalart-Allmaras Edward turbulence model while modeling the RANS equations as it lacks the sensitivity at higher angle of attack.

4.3 Comparison between two different software results

Comparison of results obtained from CFDExpert Lite^{TM} flow solver is done with ANSYS Fluent at zero degree angle of attack using the case of airship hull configuration. The drag coefficient is computed using the same boundary conditions and all other parameters are unaltered. The results obtained are formulated in the Table 1.

Table 1 Comparison between softwares

Angle of Attack = 0	Expt.	Fluent	CFDExpert Lite^{TM}
Drag Coefficient	0.00698	0.02719	0.03221

The results show that the drag coefficient obtained from CFDExpert Lite^{TM} and from Fluent are close to each other compared with the experimental and shows deviation of 15.58% within themselves which is deemed acceptable.

4.4 Effect of Skin-Friction and Pressure Drag Coefficients

Figure 8 shows the comparison of components of total drag coefficient consisting of skin-friction drag coefficient and pressure drag coefficient.

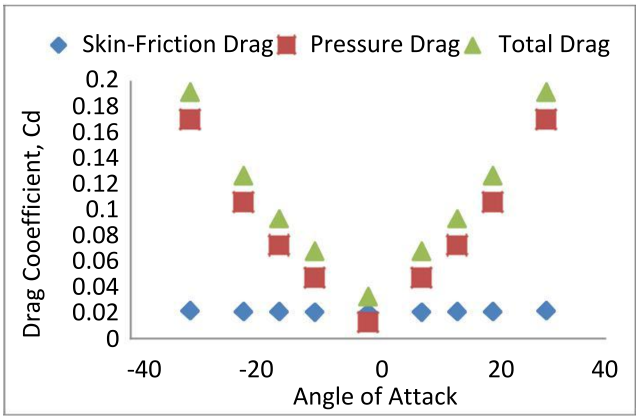


Fig.8 Comparison of skin-friction and pressure drag coefficients.

It is seen that the skin -friction drag coefficient remains nearly constant and is not affected with change of angle of attack. The pressure drag coefficient varies with angle of attack and has increasing contribution in total drag coefficient with higher angle of attack.

4. Conclusions

The numerical computations have been performed with Reynolds Averaged Navier-Stokes equations to estimate the aerodynamic characteristics of ZHIYUAN-1 airship. Computational analysis of only airship hull configuration is presented in this study. The obtained aerodynamic coefficients agree well with the experimental coefficients at lower angle of attack with deviation of 10.24%. But with higher angle of attack, the deviation between computed and experimental coefficients is found to increase. Same results are obtained with the use of different solver. This variation has been assumed due to the limitation of RANS turbulence model for higher angle of attack and thus use of improved turbulence model is suggested for such cases. Also, the important finding is that, the total drag for ZHIYUAN-1 airship is entirely due to pressure drag as the skin-friction drag remains constant at all angle of attack.

LES (Large Eddy Simulation) will be useful to predict more accurately the aerodynamic coefficients at higher angle of attack. The study of airship with hull-fin-gondola configuration will be helpful in understanding the effects of additional appendages and protuberance to bare hull.

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