Computational Fluid Dynamics Analysis of Non Slender Cropped Delta Wingsuit

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Abstract

At present, only hand-full of research work on design and development of wingsuit exists in the open domain and "sew and fly" approach is still used. In this study, CAD software Solid works was used to design the wingsuit model, using a Gottingen 228 airfoil of aspect ratio 1.05. Ansys Fluent solver was utilised to solve the Reynolds Averaged Navier-Stokes (RANS) equations with a k-? turbulence model. In this study the wingsuit is assumed to be flying at a free-stream velocity of 40 m/s. Detailed simulations were recorded at different angles of attack till stall angle to give an insight into the flow dynamics of the wingsuit. Computations showed that the wingsuit had a maximum lift coefficient of 2.4 and reached a stall angle of 40 degrees. The results were compared with the experimental and CFD results of existing literature in the open domain. The non slender delta wingsuit performs extremely well giving a lift coefficient of 2.4 and C_L/C_D of 6.7. The results were validated by comparing them with flat plate results of AR 1.0 and non slender cropped delta wing results of existing literature. A good agreement in terms of trends was obtained for C_L and C_D which indicates that proposed wingsuit should perform well aerodynamically under typical wingsuit flying conditions.

Index terms—

1 Introduction

ingsuit flying is a sport in which a human being dives from a specific height ranging from 10,000 ft to 22,000 ft and with the help of enhanced surface area high lift is generated. It has always been the desire of human being to fly like a bird, an early attempt to achieve the same was made on 4 February 1912 by a 33-year-old tailor, Franz Reichelt, who designed a wingsuit that was a combination of parachute and wing, to test the efficacy of his wingsuit he jumped from the Eiffel Tower. This experiment proved deadly and he died by hitting his head first opening a measurable hole in the frozen ground **??**1]. Rex G Finney of Los Angeles, California, made an attempt to achieve higher horizontal distance and maneuverability by wearing a wingsuit in early 1930 **??**1]. Similarly, many attempts were made to fulfill the desires of human being to fly like a bird. Early wingsuits were made up of canvas, wood, silk, steel, and whalebones and few "Birdmen" like Clem Sohn and Leo Valentin, claimed to have glided for miles though proof of their claim was never provided. Till, 1990s very limited progress was made in design and development of wingsuits and were mainly restricted to sports and fun activity with limited horizontal and man oeuvre capabilities. The wingsuit design was revolutionized by modern wingsuit developed by Patrick de Gayardon of France, his wingsuit was tested in a vertical wind tunnel but it did not went into production due to reasons unknown but peculiarity of his design was increased wing area between the legs and arms. Kuosma established Bird-Man International Ltd. the same year. Birdman's "Classic", designed by Pe?nik, was the first wingsuit offered to the general skydiving public **??**1]. Michael Abrams in his book Birdmen, Batmen, and Sky-flyers states that if piloting an aeroplane is considered to be flying than to row a canoe must be like swimming. This statement in itself gives out the desires of human to fly like a bird. Wingsuit flying gives human an opportunity to fly like a bird and is completely different from other propelled gliders be it Jet packs, hang gliders or small aeroplanes [2]. The major difference between presently used hang gliders and wingsuit is the ability of wingsuit to provide glide capability without adding weight of the motor or propeller. The sport of wingsuit provides the Skydivers to use the aerodynamic shape of the wingsuit to develop lift and obtain high glide ratio that is higher C__L/C__D ratio at a given angle of attack [3].The commercial era of wing suit began in 1999, when Jari Kuosma of Finland and Robert Pe?nik of Croatia designed and created a wingsuit that was more safe and feasible to all skydivers [4,5]. The development of an effective wingsuit has been a grey area as very limited researchers have worked upon investigating the design of a wingsuit which is quite evident from the fact that very limited research work is available in open domain to estimate the current status of research concluded in this field. With advent of computational fluid dynamics, it has become possible to design and simulate the wingsuits in actual operating conditions but still a lot of work is W required to be carried out to compare research work with existing literature and draw logical conclusions for increasing the aerodynamic efficiency of future wingsuit. The aim of this study is to carry out an extensive literature review to first establish the existing work carried out by researcher to improve the aerodynamic efficiency of the wingsuit and use these results in designing an aerodynamically efficient wingsuit using the CFD tools and validate the same with existing literature.

2 II.

3 Wingsuit Flying Conditions

Though, a very limited literature is available to establish concrete operating conditions in which a Skydiver operates but it generally varies fom 30-50 m/sec [3]. In literature also the researchers have used a variety of flow velocities ranging from 20-80 m/sec which means Re is drastically different in each of these research works. Geoffrey Robson et al [6] in their work have used horizontal velocity of 35 m/sec to 45 m/sec. Keeping this in mind in this study the flow velocity was chosen to be 40 m/sec. Also, the altitude was assumed to be 10,000 ft which generally aligns with the flying altitudes of the skydivers.

4 III.

5 Aerodynamics Theory a) Aerofoil Aerodynamics

Before starting the designing of a Wingsuit which is a 3D wing, it is pertinent to understand the flow physics involved in generation of lift by an aerofoil. An aerofoil is an cross-section of a wing and is used to understand the 2D aerodynamics, in other words aerofoil has an infinite span i.e no wingtips. Figure **??** explains the basics of lift generation by an aerofoil, as shown the incoming air makes an angle with the aerofoil thus creating change in flow velocity due to change in streamlines which in turn creates a pressure difference thus creating upward force called lift. The weight of the aerofoil is taken as the drag, the aerodynamic efficiency of an aerofoil is seen from its ability to produce higher lift with little drag i.e. higher C__L/C__D ratio [7].

6 Figure 1: Aerofoil Aerodynamics

Understanding of aerofoil aerodynamics is critical in wingsuit design as it helps in selection of aerofoil for designing wingsuit to meet the requirement of higher glide ratio. Thus, by making use of higher lift generation capability of an aerofoil i.e. higher camber the skydivers can achieve higher range and can even gain altitude by suitable maneuvers.

7 b) Wingsuit Aerodynamics

Though the only difference between aerofoil aerodynamics and wingsuit aerodynamics is that the later is a 3D wing with finite aspect ratio (AR) as shown in Figure 3. In Figure 3, as indicated the space between the skydivers hand and legs is utilized for making the wing segments using a particular shape of a selected aerofoil. The basic wing theory involved in wingsuit aerodynamics, is the skydiver on jumping from the aeroplatform or a plataform i.e. aeroplane or cliff etc, dives into the air and the wingsuits makes use of the ram air and takes the shape of the aerofoil, such as Tony Uragallo's Wingsuit that uses the same concept and takes the shape of an aerofoil using ram air and gives a glide ratio of 3.6 to 1 [8]. This camber is then used to change the flow of the streamlines which is turns produces pressure difference hence the lift. The wingsuit model designed and tested in this study has been created using GoE 228 aerofoil cross-section. In order to validate the CFD test set up being used for carrying out CFD analysis of the proposed wingsuit in this study, it is desirable to test this setup on 2D GoE aerofoil and then compare these results with the results available for the same aerofoil under similar Re conditions in open domain. As in case of a 2D aerofoil there is no effect of induced angle of attack and the angle of attack of the incoming air is considered to be the angle of attack for the aerofoil. But as wingsuit is 3D in nature it will experience the induced angle effect due to the downwash thus to obtain an effective angle of attack the same needs to be subtracted from the geometric angle of attack as given below?? ?????? = ?? -?? ??

Where ?? ?? is the induced angle of attack and ?? is geometric angle of attack. Also ?? ?? can be expressed in terms of ?? ?? and aspect ratio (AR) and is given below?? ?? = ?? ??

8 ????????

Also the slope of the lift curve is an indication of the aerofoils to generate lift, a higher lift slope indicates that aerfoil can generally produce higher lift at lower angles of attack. The relations between the lift slope and AR is shown below.???? ?? ???? = a = ?? 0 1+ ?? 0 ?????? (1+??)

Where a is the slope for 3D wing and ?? 0 is the slope for 2D aerofoil cross-section of the wing. ?? varies from 0 to 0.25, in the present case its value is taken as 0.

IV.

9 Literature Review a) Results from existing literature

Wingsuit designed and tested in this study is developed using an exact aerofoil cross section. The wingsuit being a 3D wing behaves differently than an aerofoil because of the obvious reasons. A very limited experimental as well as computational research work on design and development of wingsuit exists in the open domain. Nyberg [9] in his research work studied flow over Apache wingsuit at velocity ranging from 40 m/sec to 83 m/sec, he observed that the stall angle was approached at around 40 degrees with max glide ratio of 4.2. He also, observed that with increase in velocity the performance of the wingsuit reduced due to increased flow separation and higher drag. He in his study found some instability in wingsuit at higher speeds which he contributed to the computational error and not the wingsuit design. Berry et al [10] in their study conducted wind tunnel testing on a novel wingsuit design and compared it with a modified design with a forward wing. They observed that there was a increase in glide ratio with increase in angle of attack in the original wingsuit but addition of forward wing reduced the glide ratio despite having a higher lift coefficient. They contributed this to the increased profile and induced drag generated by the forward wing added to original wingsuit. Also, the max glide ratio achieved was in the range of 2.5. Also, B. Read et al [11] designed and tested Icarus wingsuit which was scanned using laser to capture the entire Icraus wingsuit model. The same was then used to carry out CFD analysis to study the flow field and aerodynamics of the wingsuit. Also, they carried out wind tunnel testing to validate the results so obtained from the CFD analysis. They used the CFD and wind tunnel results to modify the design of the wingsuit to enhance the lift to drag ratio and were able to design "Athena" helmet to improve the gliding performance of the skydiver. Geoffrey Robson et al [6] performed longitudinal stability analysis of a jet powered wingsuit. They were able to obtain real flight data of the wingsuit on which their analysis was based. They contributed phugoid mode as the primary source of instability during the jet powered flight. Based upon their analysis they proposed use of computer aided thrust vectoring methodology to overcome the phugoid instability and improve the performance of the wingsuit. Shields et al [12] studied effect of slideslip on low aspect ratio wings, as the present study also involves wingsuit of lower aspect ratio certain important lessons are drawn from their studies to improve performance of the wingsuit. They observed that sideslip effects the overall performance of a wing, they ascertained this by conducting wind tunnel testing of flat rectangular wing and verified the results using surface tuft flow visualization. Ansari et al [13] conducted a series of wind tunnel experiments on wingsuits and validated that the same using CFD. They observed that the refines wingsuit having inflated surface performed better as compared to plain surface. Though the performance of the wingsuit was below par but they concluded that the surface finish of the wingsuit is an important parameter and has a important role in lift to drag ratio.

10 b) Comparative Analysis

To better understand the effect of flow velocity and angle of attack on low aspect ratio wingsuit, results from the existing literature [9,13] have been extracted and are plotted as shown in Figure 2. It is observed that with increase in angle of attack the glide ratio tends to decrease and the maximum glide ratio is achieved in the range of ? = 5 0 to 15 0 . The maximum glide ratio is in the range of 4 to 4.2, which is considered to be very good in terms of wingsuit flying. The availability of research work on improving the performance of wingsuit is very limited and still commercially the approach of developing a wingsuit is "Sew and Fly". Though, few researchers have used CFD analysis to design and study the behavior of a wingsuit and used these results to improve the lift to drag ratios but in most cases these designs are not practically feasible and cannot really be used to produce wingsuits e.g. Ferguson et al [16] designed the wingsuit using GoE 228 aerofoil but they ignored the effect of head, arms and feet of the wingsuit flyer thus despite of obtaining a ?? ?? /?? ?? of 7.7 their wingsuit is not feasible to manufacture and be of use to skydivers. Keeping this in mind the wingsuit in this study was designed to factor in the effect of head, body and feet of the skydiver and at the same time it must give good L/D ratio which is higher than the commercially available wingsuits. Also, as the wingsuit flying velocity ranges is generally from 30 -50 m/sec [5], the flow velocity was kept at 40 m/sec such that the results so obtained can be validated and compared with the existing literature.

V.

11 Wingsuit Design

In order to conduct CFD analysis of a wingsuit, it is pertinent to first design the geometry of the wingsuit. As discussed earlier, the wingsuit takes the shape of an aerofoil using the ram air thus the first step in designing the wingsuit is to select an aerofoil. Since, the aim of this study is to design and develop high range and endurance capable wingsuit it is an inescapable requirement to select a highly cambered aerofoil. Also, in reality wingsuits are flexible in nature but for the purpose of CFD analysis the designed wingsuit is assumed to be of rigid nature. The wingsuit is assumed to be an ideal approximation of the commercially available wingsuits. In this study the typical parachute backpack has been excluded as it is assumed that the flow separates from the head and area behind the head does not really participates in generation of the lift due to the flow seperation from the head.

12 a) Selection of Aerofoil for Wingsuit Design

To obtain high lift to drag ratio in a wingsuit selection of correct aerofoil is most important. Though a number of highly cambered aerofoil are available which can provide high lift but it is also important to study the associated drag and feasibility of using such aerofoil for wingsuit design. In this study, a well-researched GoE 228 aerofoil has been selected as Ferguson et al [16] found in their study found that the aerofoil produces high L/D ratio. To validate the lift and drag force produced by GoE 228 aerofoil, a CFD analysis of GoE 228 aerofoil was carried out in ANSYS software to obtain the results for lift and drag and the results so obtained were compared with results available in open domain **??**14] for GoE 228 aerofoil under similar Re conditions. Figure 5 gives out the details of the GoE 228 aerofoil, the aerofoil coordinates were obtained from open source and these were then imported into SOLIDWORKS software to generate the GoE aerofoil.

13 i. Mesh Creation for GoE 228

A mesh or grids are the tools used by the user to define the locations near the body or aerofoil in this case where the flow equations are required to be solve. As, it is not possible to solve the flow equations at each and every point in the computational domain so it is important to have a denser mesh near the body, in the wake region and areas where large gradient exits. To obtain consistent and accurate results, meshing quality needs to be of highest order i.e. a denser mesh is desired especially near the geometry. At the same time, domain far away from the geometry can have a less dense mesh this helps in reducing the computational power required to solve the flow equations and helps in achieving faster results. An all triangles method was used for creation of the mesh at the same time Edge sizing of 12000 divisions was utilized to refine the mesh. Also, refinement factor of 2 was used to create a finer mesh with 2.5 million elements especially near the geometry, in its wake region and around the leading edge where the flow separation is dominant the same is shown in Figure 4. GoE 228 as shown in Figure 4 is a highly cambered aerofoil and produces high lift at lower angles of attack. Since, this study aims at designing and development of high glide ratio wingsuit, it is pertinent to study the aerodynamics of the aerofoil selected for designing the wingsuit. Also, CFD analysis of the aerofoil acts as an instrument to validate the CFD model and setup to be used further CFD analysis of the proposed wingsuit. If a good agreement is reached between the results obtained from CFD analysis of the GoE 228 aerofoil and the results available in open domain [14] under similar Re regime then it can be assumed that the CFD model is consistent. The CFD analysis of the GoE 228 aerofoil is carried out using Ansys software. The aerofoil coordinates were imported in SOLIDWORKS software to create the aerofoil and then the same was imported to ANSYS workbench to create the geometry as shown in Figure 4. The 2D enclosure was selected to be of 20m around the aerofoil so as to obtain disturbance free flow and minimum wall effect.

14 c) GoE 228 Aerofoil results and validation

The Reynolds number for the 2D aerofoil was set to 10 5 . k-ð ??"ð ??" Turbulence Model was used for carrying out the CFD analysis and the results so obtained were compared with the results available in the open domain **??**14]. It was observed that the lift is obtained at zero angle of attack which is obvious as GoE 228 is a highly cambered aerofoil. As shown in Figure 6 the lift coefficient is observed to increase with increasing angle of attack till 14 degrees and stall is reached at 15 degrees. The results from CFD analysis were then compared with the results available in open source **??**14] and there seems to be good agreement between the two results with max error of 9 % at 4 degrees was observed which can be attributed to the fact that the data available in the open source is for Re~2.5 x 10 5 but in this study the Re no is of the order of 2 x 10 5 and also to computational error, though a complete agreement in terms of trend for lift coefficient was obtained. Similarly, plot was obtained for coefficient of drag against angle of attack as shown in Figure 7, it was observed that the drag coefficient increases with increase in angle of attack. This increase is gradual till 6 degrees beyond which a rapid increase in drag coefficient can be seen. This rapid increase can be attributed to increase in profile drag as with increase in angle of attack beyond 6 degrees the flow tends to separate from the leading edge. Though the effeciveness of the CFD model to be used was validated by comparing the results of the CFD analysis of GoE 228 aerofoil with open domain results but still it is pertinent to establish that the results are independent of mesh size. To ascertain the quality of the results obtained from the CFD analysis of the aerofoil a mesh independence test is carried out. This validates that the results are independent of number of elements, in the present study the results for GoE 228 were obtained for 0.1Million and 0.5Million elements for the given geometry. The results so obtained are appended below. The value of lift and drag coefficient was measured at 6 o and 12 ?? AoA respectively for both 0.1million and 0.5million element mesh. It was observed that error of less than 1 percent was observed between the two values. This validates that the setup is independent of the size of the mesh and also the setup used can be utilised for CFD analysis of 3D wingsuit which is also designed using GoE 228 aerofoil.

15 e) 3D Wingsuit Design in SOLIDWORKS

The wingsuit is designed in SOLIDWORKS 2019 software for an average human being having height of 1.7 m and span of 1.8 m thus making the aspect ratio of the wingsuit 1.05, the parachute on the back of the skydiver has been neglected as it is assumed that the flow separation occurs at the head and area behind the head will not participate much in the lift generation. Figure 7 gives out the geometric details of the wingsuit, initially GoE coordinates with 1.7m chord were imported to make the centre aerofoil followed by incremental decrease in chord by 0.05m till the wingtip where chord is 0.4m. A total of 14 aerofoils were used to create one side of the wing. Rear wing to accommodate the feet of the skydiver were created using the same GoE aerofoil with chord of 0.25m as shown in Figure **??**. The entire geometry was then lofted to create the other side of the wingsuit. The simulations were carried out at 40m/s with Angle of Attack (AoA) set as 0, 5,10,15, **??**0, **??**5, **??**0, **??**5, **??**0

16 b) Computational Fluid Dynamics Simulations of

Wingsuit at 40 m/sec i. Case 1: 0 degrees AoA At 0 degrees angle of attack, the wingsuit is perfectly aligned with the flow as shown in figure 9(a) there exists a very minute variation of pressure that is within 10 units. This indicates that the wingsuit is creating very little disturbance in the flow field and wingsuit behaves as a streamline body. The airfoil section being highly cambered allows flowto remain attached with the wingsuit body as flow passes over. The rear portion of the wingsuit body has extra lift generating surfaces, which not only provides extra lift but also protects the flow from being separated at the trailing edge of the main body by creating vortexes. Sheilds and Mohseni [12], in their study of low AR wing observed creation of the wingtip vortices and attributed the same for additional lift obtained. Flow is observed to be fully attached with the wingsuit also in figure 9(c) it is observed that the strong wingtip vortices are produced which augment the lift produced by the wingsuit. These wingtip vortices are very dense having strong vorticity thus providing additional lift which agrees well with the findings of Sheilds and Mohseni [12].The results are generated for fully converged solution, as shown in figure 9. In this case the AoA is increased to 10 degrees keeping the flow velocity same. It is observed that the flow remains attached in this case also, the adverse pressure gradient is the reason for the flowseparation in general, however from the pressure contour plot as shown in figure 10(a) it is observed that pressure variation is minimal. The same is validated from the velocity plot as shown in figure 10(b) as there is minimum change in the velocity contours along the wingsuit indicating that the flow is fully attached even at an AoA of 10 degrees. In figure 10(c), it is seen that with the increase in angle of attack the strength of the wingtip vortices reduce thus the associated lift component reduces but the overall lift is increased due to the lift produced by the wingsuit has increased with increasing angle of attack. The results are generated for fully converged solution, which can be seen from the Figure 11. The AoA is set to 20 degrees for this case, with increase in AoA the bluf behaviour of the body has increased. It is observed from figure 12(a) that the variation of pressure over body with respect to surrounding is very low or it can be said that the pressure gradient is favourable. It is also observed that there exists a little increment in pressure gradient near the trailing edge of the body or rise of adverse pressure gradient leading to flow separation from trailing edge. Shields et al [12] in their study found that for low aspect ratio there is an existence of strong wingtip vortices which grow in size with increase in angle of attack. In figure 12(c), it is observed that the size of the wingtip vortex has increased at the same time it is lesser denser in nature i.e. strength of the tip vortex has reduced thus there exists an agreement with findings of Sheild et al [12] and the present study. The results are generated for fully converged solution, which can be seen from the Figure 13. As, AoA is further increased to 30 degrees, the bluf behaviour of the body has increased significantly. It is observed that the variation of pressure over the upper surface of the body with respect to surrounding is higher than the lower surface. But on the lower surface of the body the pressure variation is within the admissible range. In figure 14(a) it is observed that there exists a huge pressure variation creating wake zone near the trailing edge causing the flow to separate from trailing edge. In figure 14 (b), it is observed that there is a creation of wake zone near the trailing edge causing the flow to seperate. In figure 14(c), it is observed that the size of the wingtip vortex has further increased with increase in angle of attack and vorticity has reduced thus making the tip vortex weaker. The results are generated for fully converged solution, which can be seen from the Figure 15. As discussed above, the results from CFD analysis of the designed wingsuit appeared very promising as the flow remained attached even till 40 degrees AoA. In any study it is pertinent to validate the results from existing literature but as very limited literature is available in the open domain so to validate the trends obtained from CFD study of wingsuit these were compared with results of flat plate having AR~1 [15]. The results obtained for ?? ?? vs ?? and for ?? ?? vs ?? for inlet velocity of 40m/s at various AoA and were compared with the flat plate data. As shown in figure 16(a The ?? ?? vs ?? curve as shown in figure 18, the drag curve follows the drag curve for the flat plate till 30 degrees AoA. Although at 30 degrees flat plate encounteres stall but for commercially available wingsuit and proposed wingsuit the stall angle is around 40 degrees. It was observed that the drag coefficient of designed wingsuit is a little higher as compared to existing literature, this may be attributed to additional lift generated by the wingsuit due to the camber of the GoE aerofoil i.e. induced drag component has increased due to the additional lift thus increasing the overall drag of the body. It was observed that max ?? ?? /?? ?? is at AoA of 0 degrees (crusing AoA) which is around 6.7 and much higher than the commercially available wingsuits and flatplate. Thus, it can be concluded that the proposed design of the wingsuit performed extremely well and is likely to give higher range and endurance, which is discussed in next section.

17 VIII. Range and Endurance for the Wingsuit

As discussed above the designed wingsuit performed extremely well in comparison to commercially available wingsuit and gave a staggering ?? ?? /?? ?? of 6.7. The obtained values were used to calculate the range and endurance and then compared with the capability of other wingsuits. The range of wingsuit is the distance it travels during the glide descent. It is calculated by the formula mentioned below:

The equations of motion are given by:0 ? ?? ? ??sin?? = ???? ?= 0, ?? ? ??cos?? = ???????= 0 (1)

where ?? is the flight path angle (the angle the velocity makes with the horizontal).

If we divide one equation by the other, we get:tan?? = ? ?? ?? = ? 1 ??/?? (2)

It is observed from the above equation that the flight path angle is negative, i.e. the glide angle can be defined as the negative of the flight path angle and written as:tan?? 1 = ? 1 (??/??)**(3)**

Where (?? 1 is glide angle (and is positive).

From above it is observed that the glide angle depends only on L/D and is independent of the weight of the vehicle also the flattest glide angle occurs at the maximum L/D.a) Glide Range ?? = ? 1 ?? 2 tan ?? 1 (4)

Hence the range for gliding flight depends on the L/D and Î?"h. This means to acheive maximum range it is important to macimise the L/D ratio.Therefore the maximum range glide is flown at the minimum drag airspeed, ?? ???? .

18 b) Small Glide Angle Assumption

In most cases, the glide angle will be small for an equilibrium glide. Under these circumstances, we can make the following approximations (?? 1 « ??):cos?? 1 ? 1, sin?? 1 ? tan?? 1 ? ?? 1 ? 1 (??/??)**(5)**

The most important result of this assumption is that we can make the approximation that:?? = ??cos?? = ??, ?? = ? ?? 1/2???? ?? ??**(6)**

Hence we can use the weight in order to compute the airspeed. Without this assumption the calculations can become more difficult.

19 c) Rate of Climb (Sink)

The rate of climb is given by, ? ?= ??sin?? (7) We can eliminate sin?? to get,

We can note the rate of climb is negative (hence a sink rate), and that it is directly related to the quantity, ?? ?? /?? ?? 3/2 . Therefore, if we want to minimize the sink rate, we must minimize the quantity, ?? ?? /?? ?? 3/2 i.e. if we minimize the sink rate, we maximize the time to descend or maximize the time aloft, or endurance.

20 d) Time to descend

The descent rate depends on the altitude i.e. on ??. It means, density variations needs to be included to obtain exact solution for the time to descend. If change in density is minimal than density can be assumed to be constant, at the same time if AoA is assumed to be constant throughout the flight then ?? ?? and ?? ?? also become constant. Under these circumstances and assumptions the rate of descent is constant. Thus we have time of flight given by, ?????? = ? Î?"? ? ? (10) where ? ? is assumed constant. Generally the value of ? ? used is that calculated for an altitude halfway between the initial and final altitudes.If large altitude changes are involved, the above equation can be used for several smaller increments in altitude and the results obtained using the above formulas are apended below. It is observed that the designed wingsuit in this study outperforms the wingsuit results available in the literature by a good margin. The range is increased by 8 km while the endurance has increased by 5 mins.

21 IX.

22 Conclusion

The desire of human being to fly like a bird has always been an area of interest but a very limited research work exists in the open domain that can be said to be of conclusive nature to draw some lessons that can help researchers in designing high lift generating wingsuits. In the present study GoE 228 aerofoil was selected for designing the wingsuit as the same was found to be aerodynamically very effective in the research work carried out by Ferguson et al [16]. The wingsuit was designed such that it is feasible to manufacture the same and is of practical use to the skydivers. CFD analysis was carried out at velocity of 45 m/sec at various angles of attack till stall. The results so obtained were then compared with the data extracted from the existing literature. It was observed tht the proposed wingsuit performed extremely well and gave a ?? ?? /?? ?? of 6.7 with range of 20.421 km and endurance of 22.21 minutes. This study paves the path for future researcher's in terms of effective design of the wingsuit and suitability of the design for manufacturing. [1] [2]

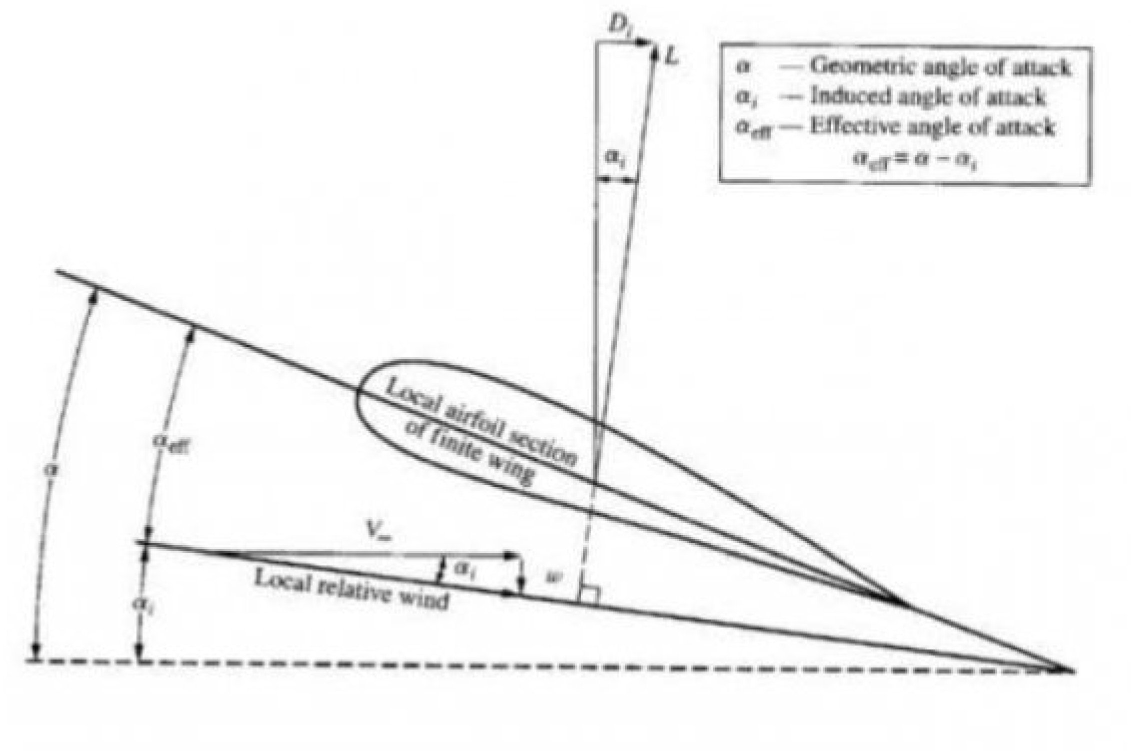

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Figure 1: Figure 2 :

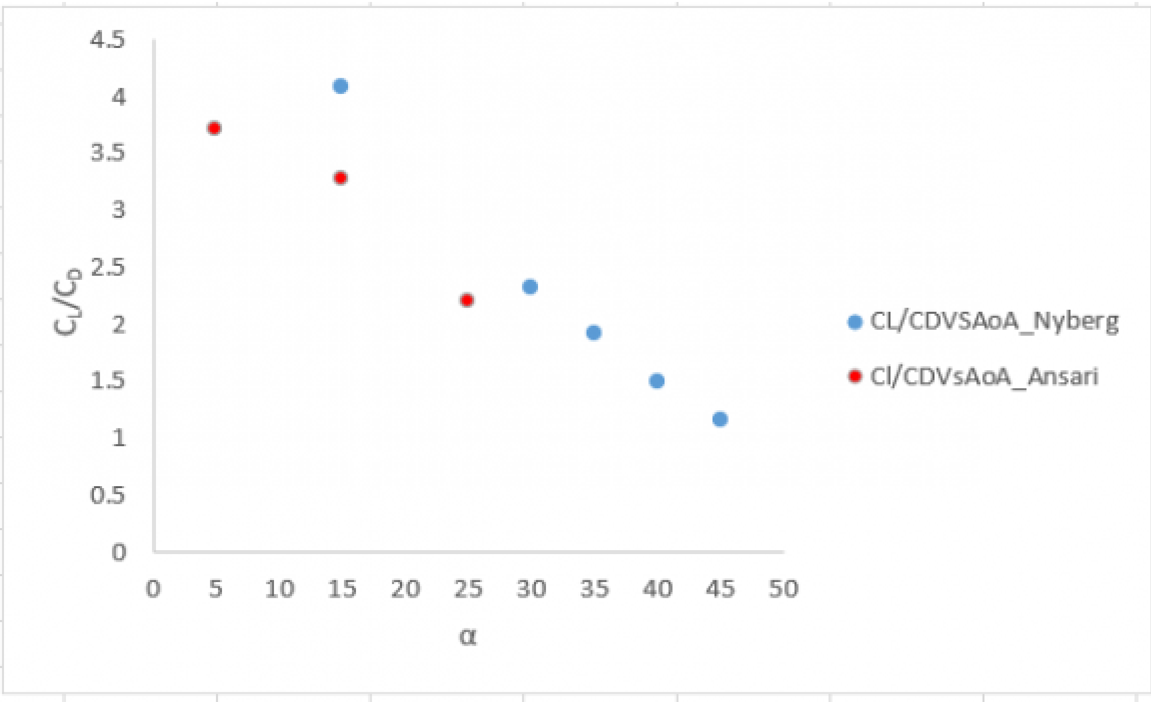

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Figure 2: Figure 3 :

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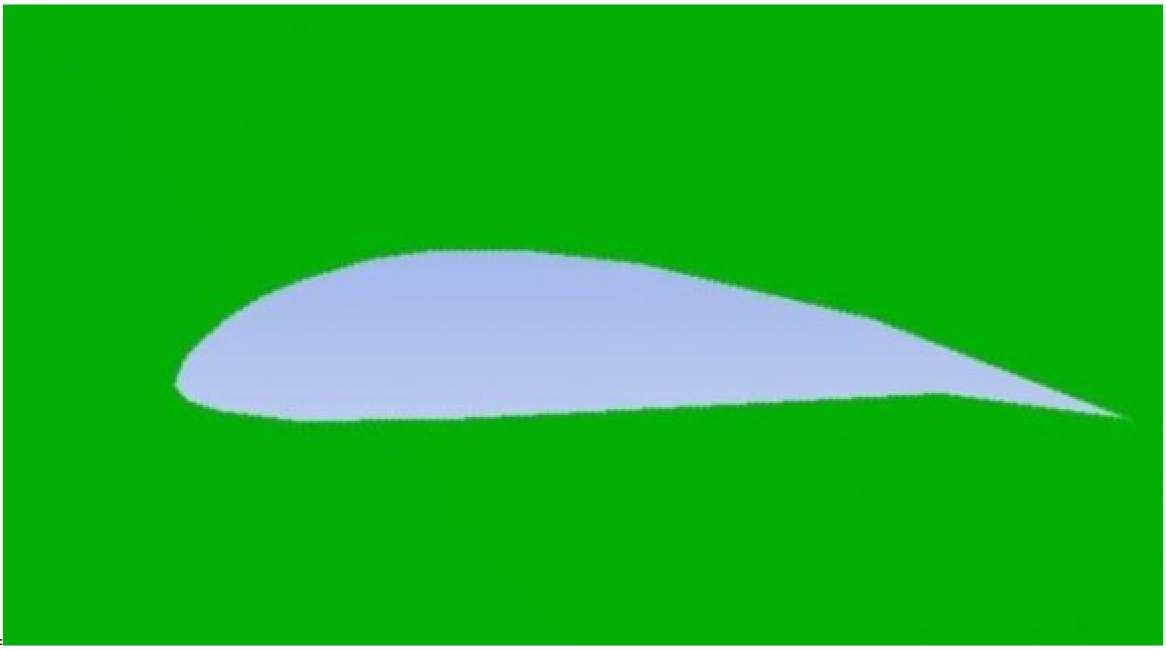

Figure 3: Figure 4 :

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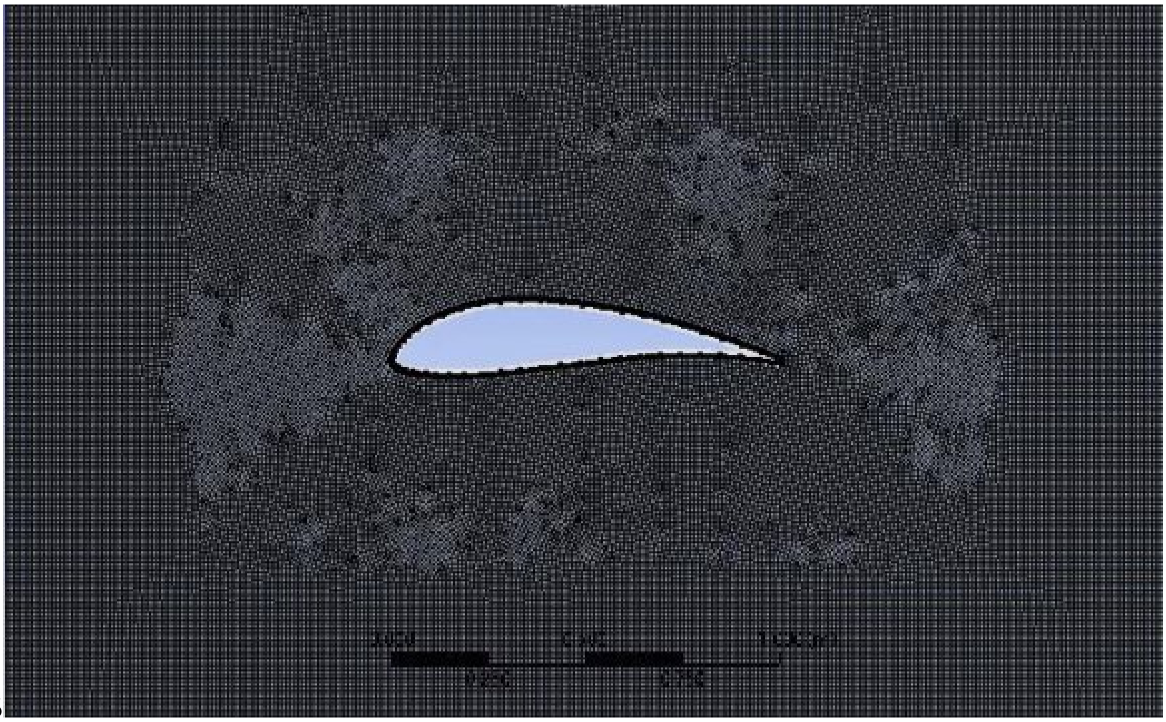

Figure 4: Figure 5 :

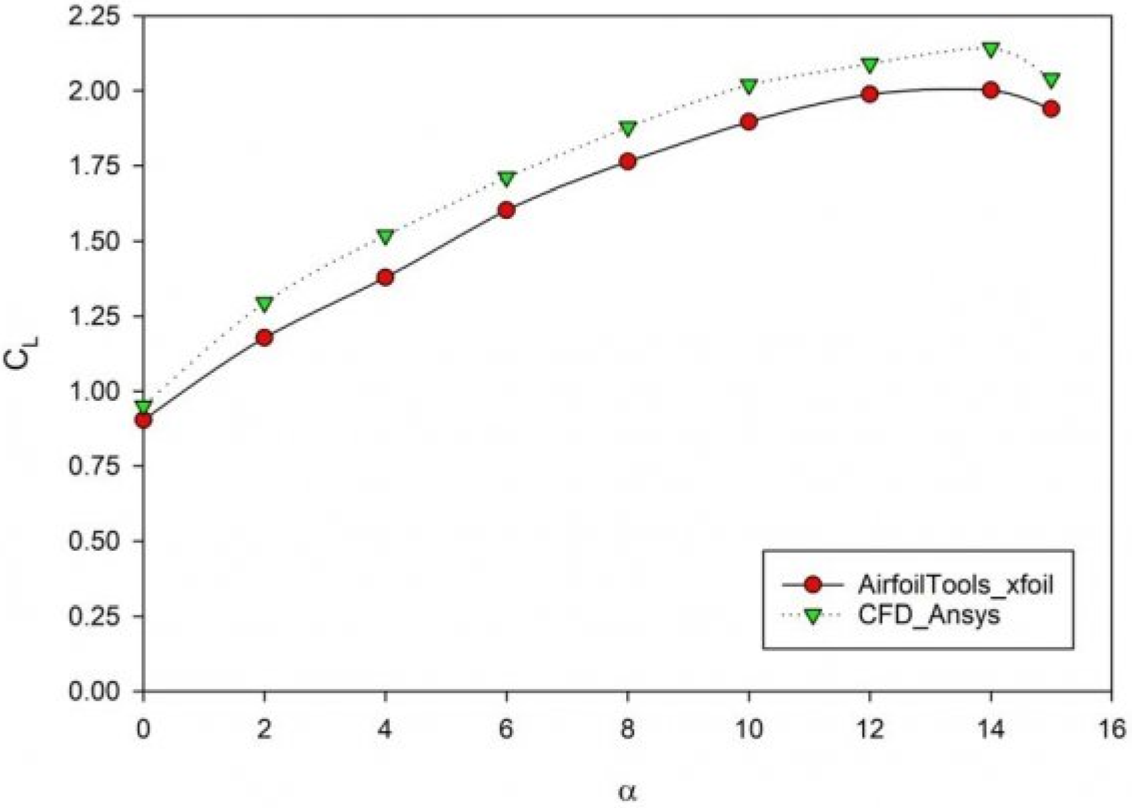

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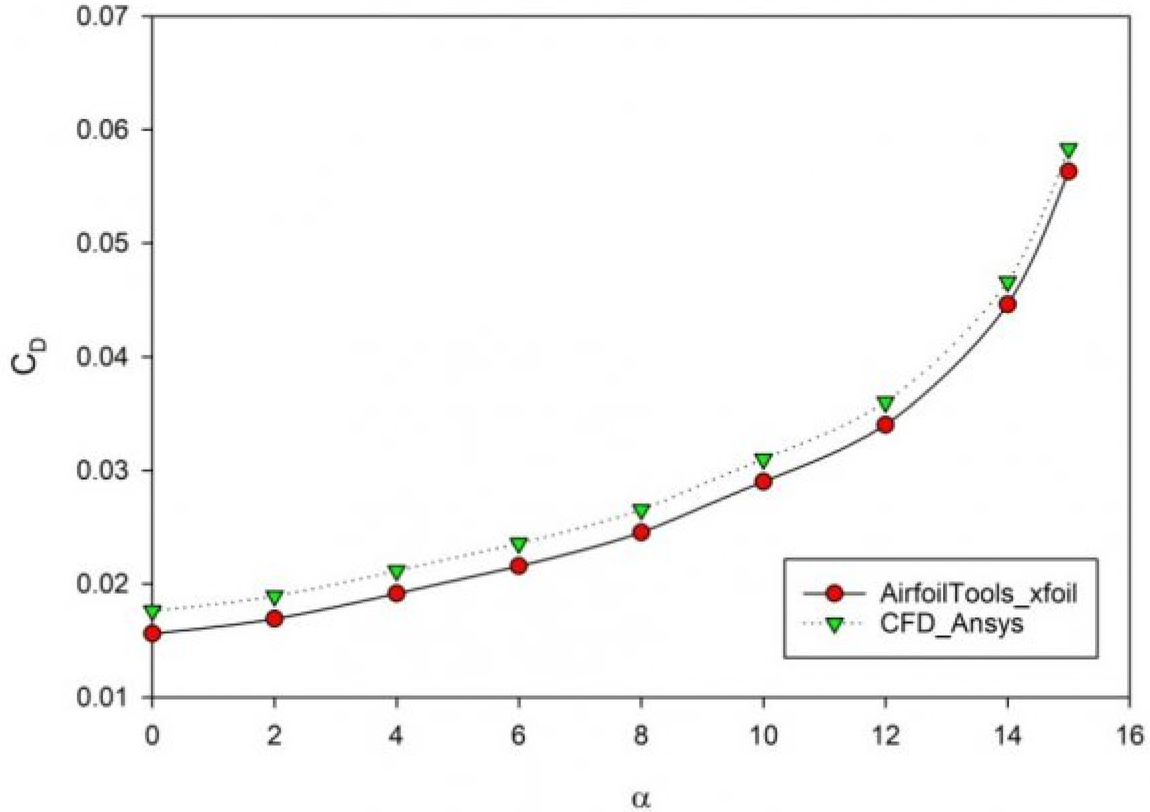
Figure 5: Figure 6 :



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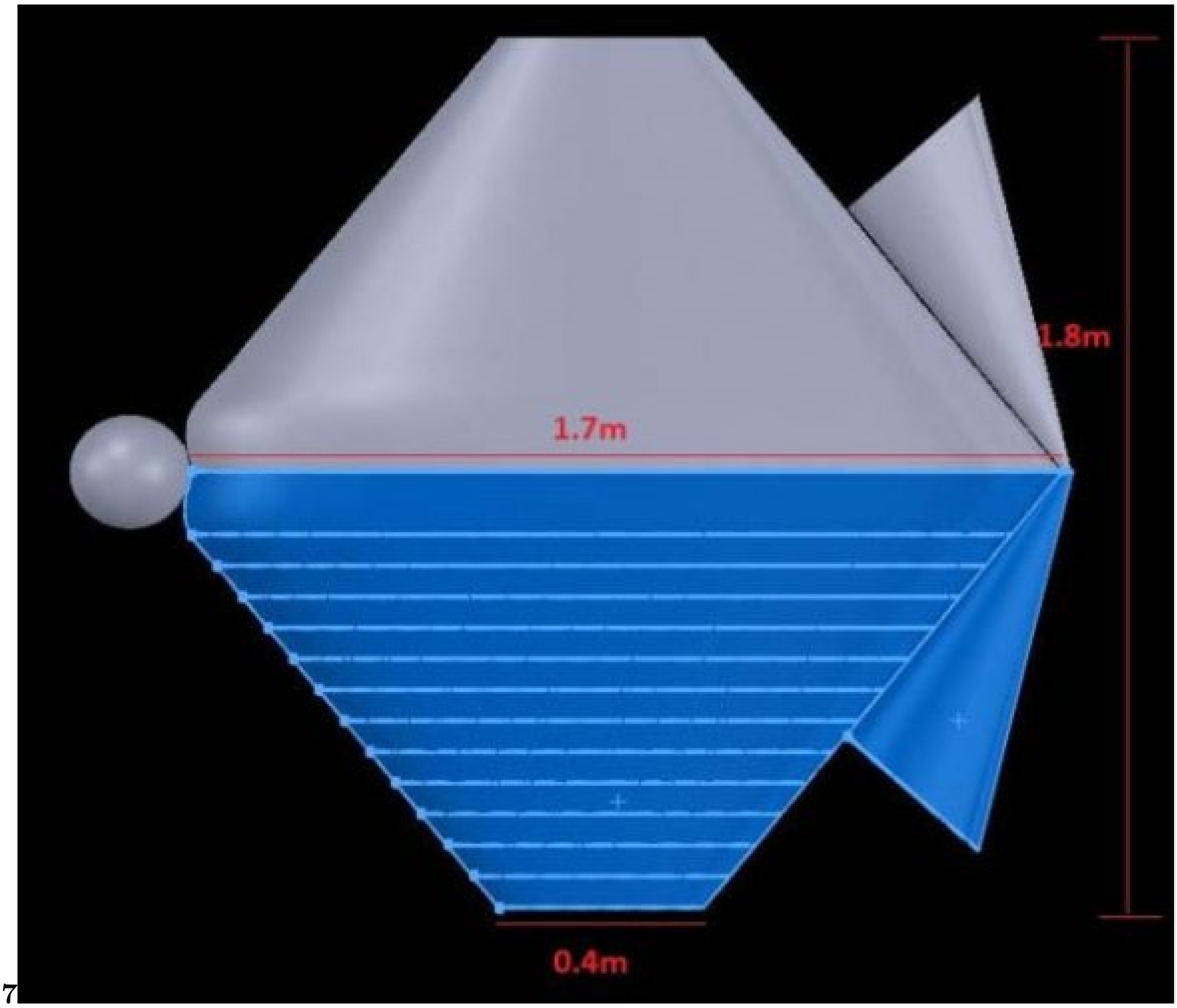

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Figure 7: Figure 7 :

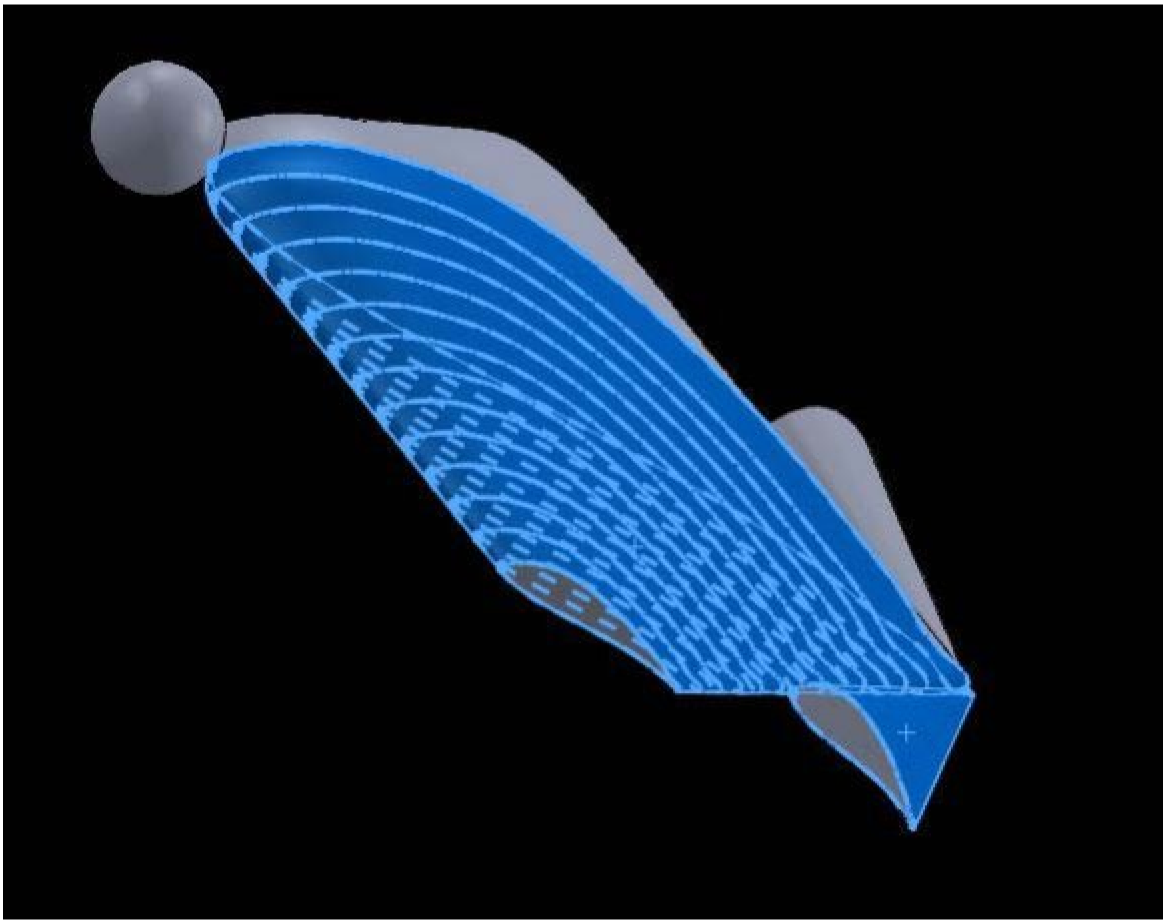

Figure 8:

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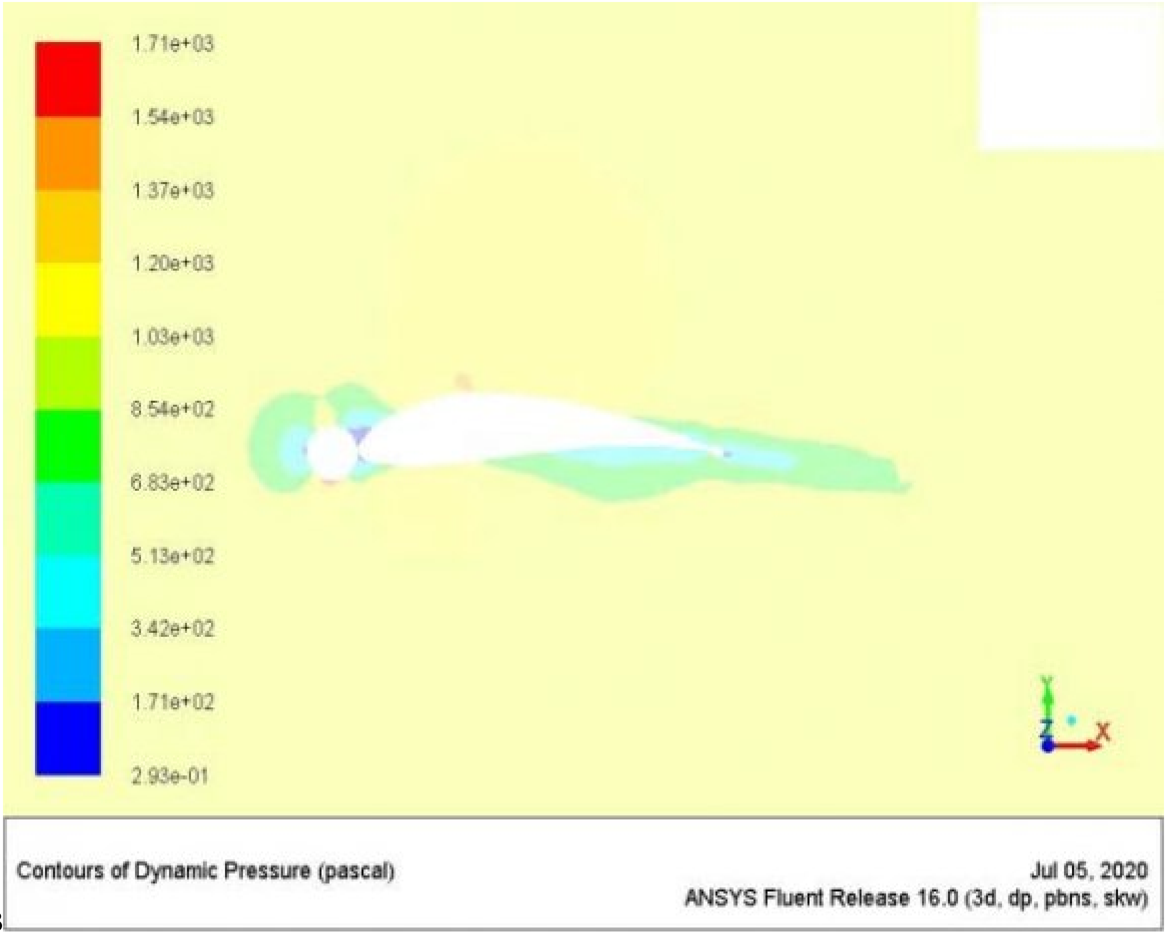


Figure 9: Figure 8 (Figure 8 :

9

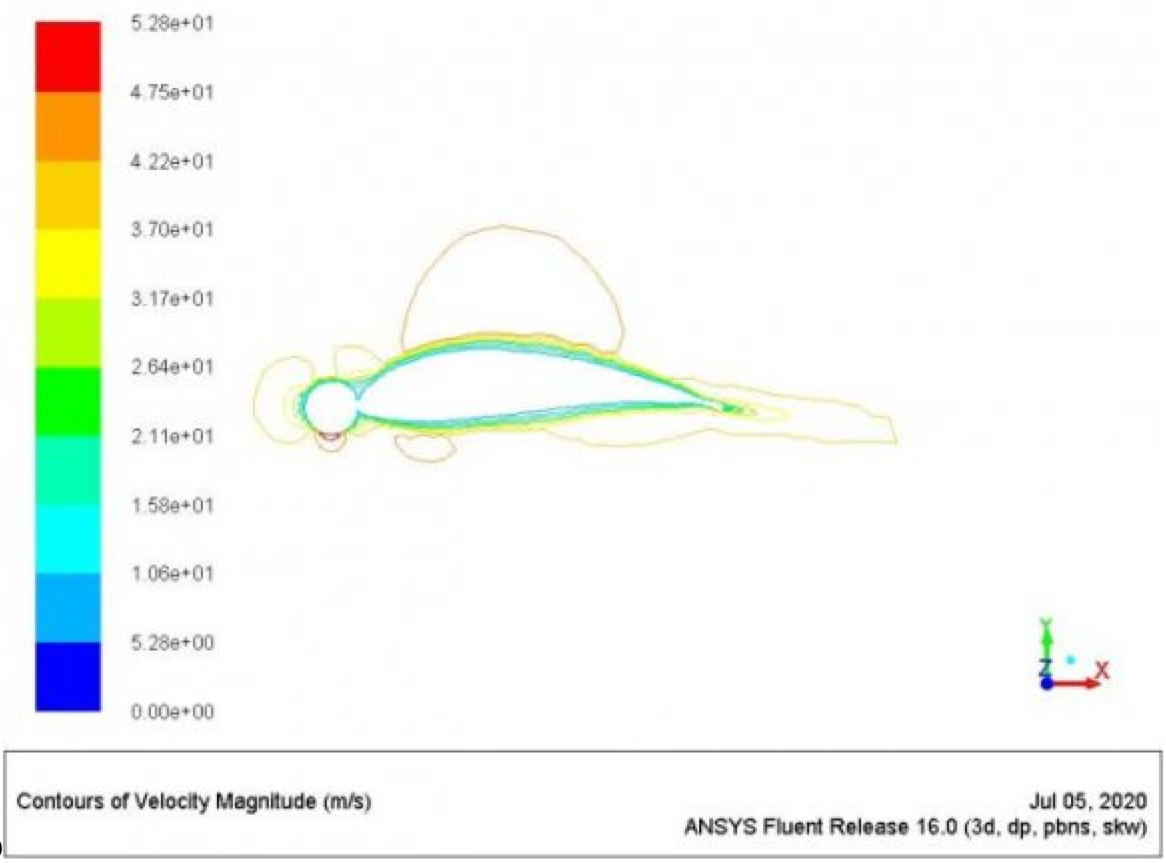


Figure 10: Figure 9 :

10

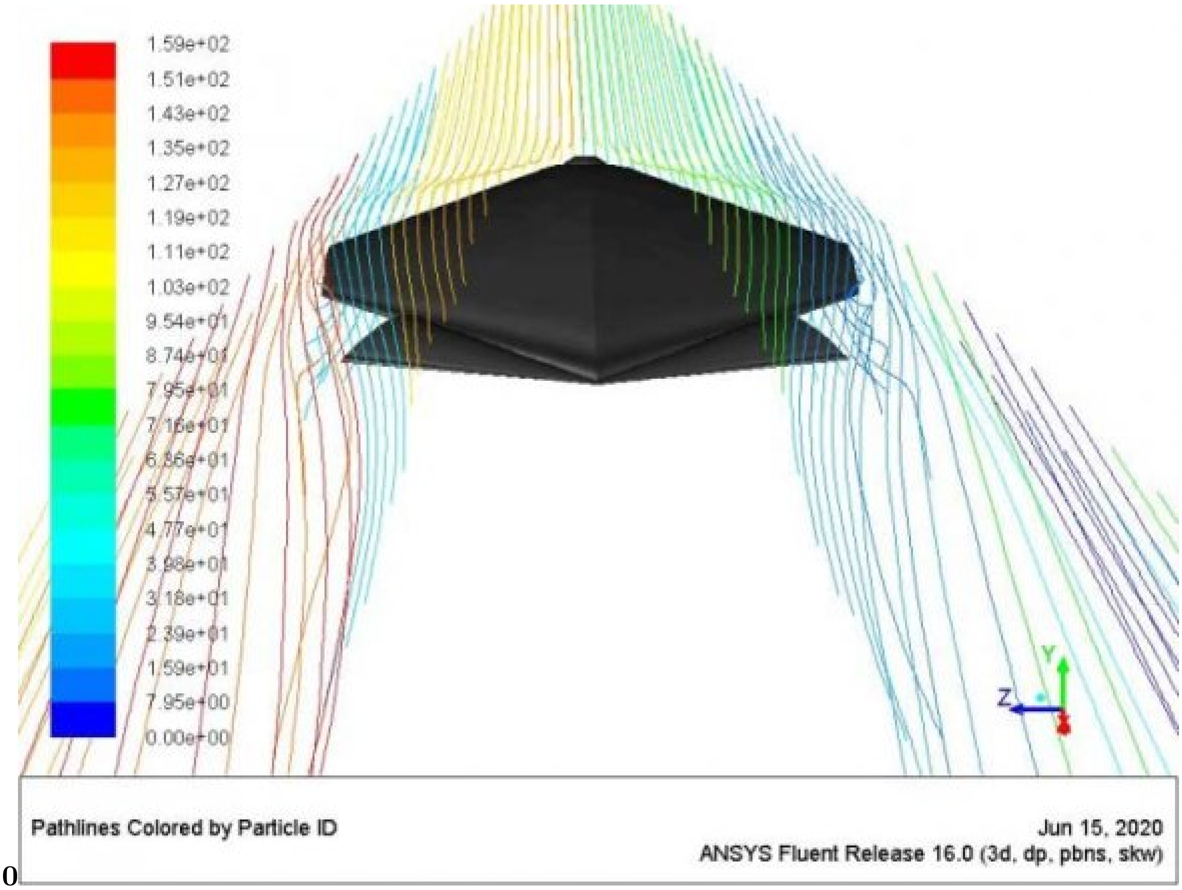
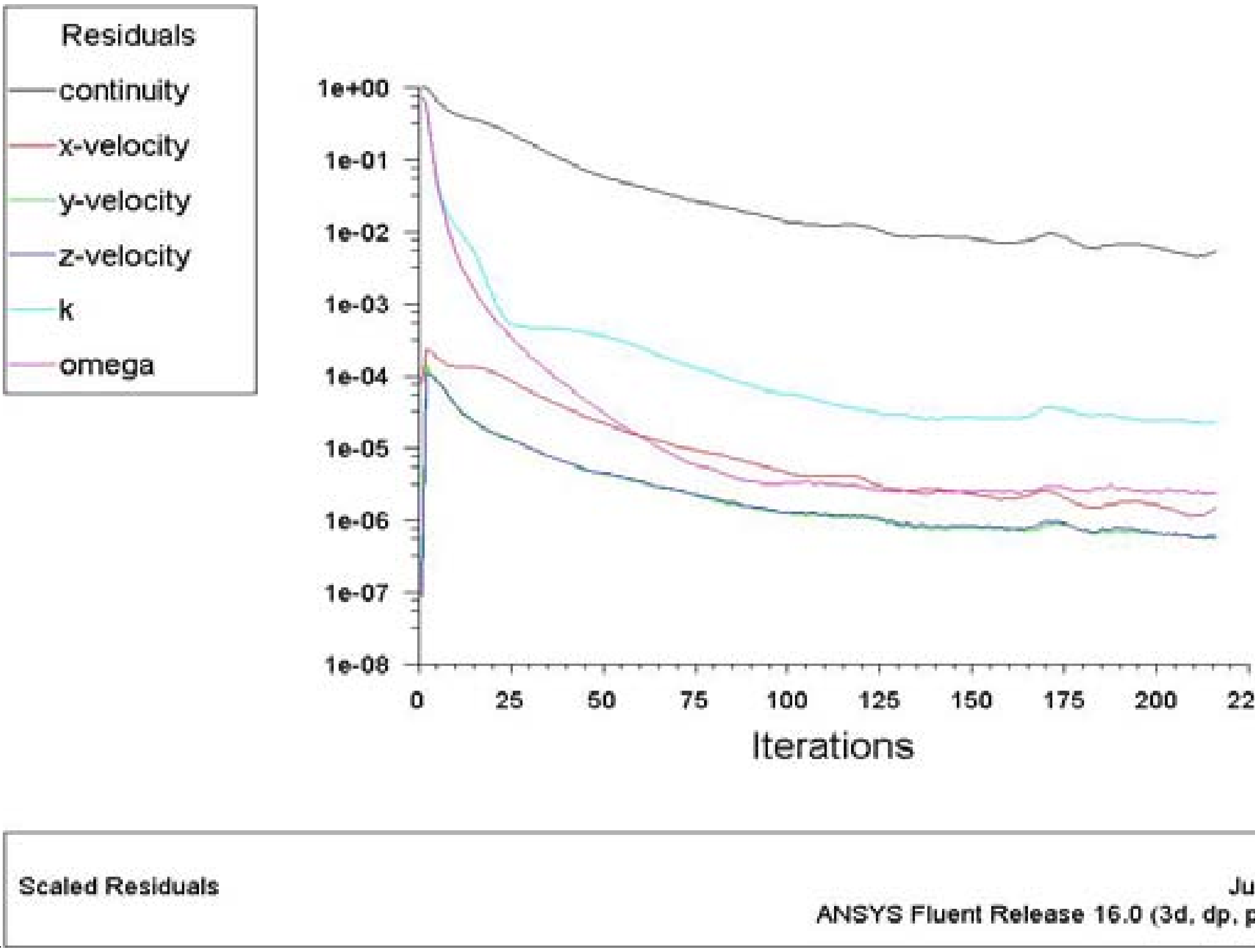


Figure 11: Figure 10 :

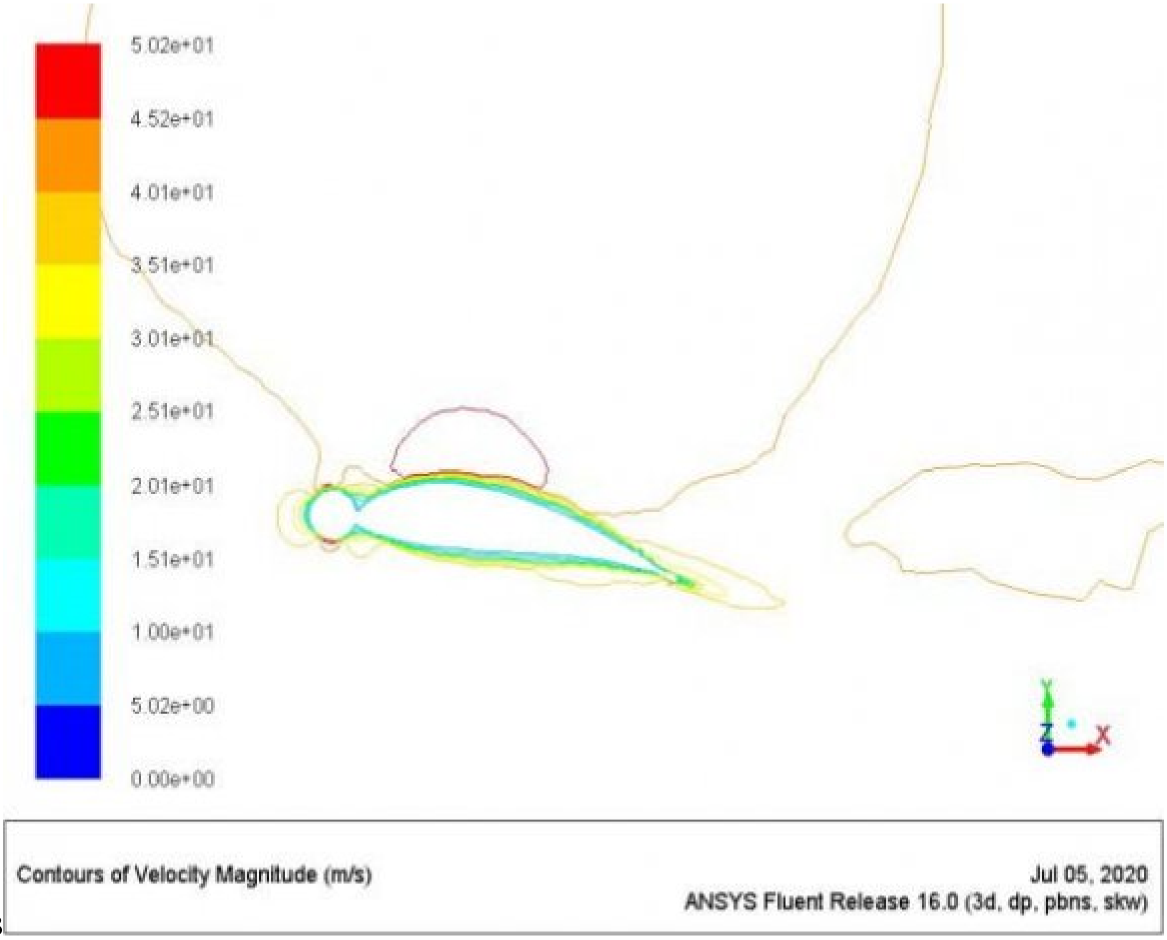


11

Figure 12: Figure 11 :

12

Figure 13: Figure 12 :



13

Figure 14: Figure 13 :

14

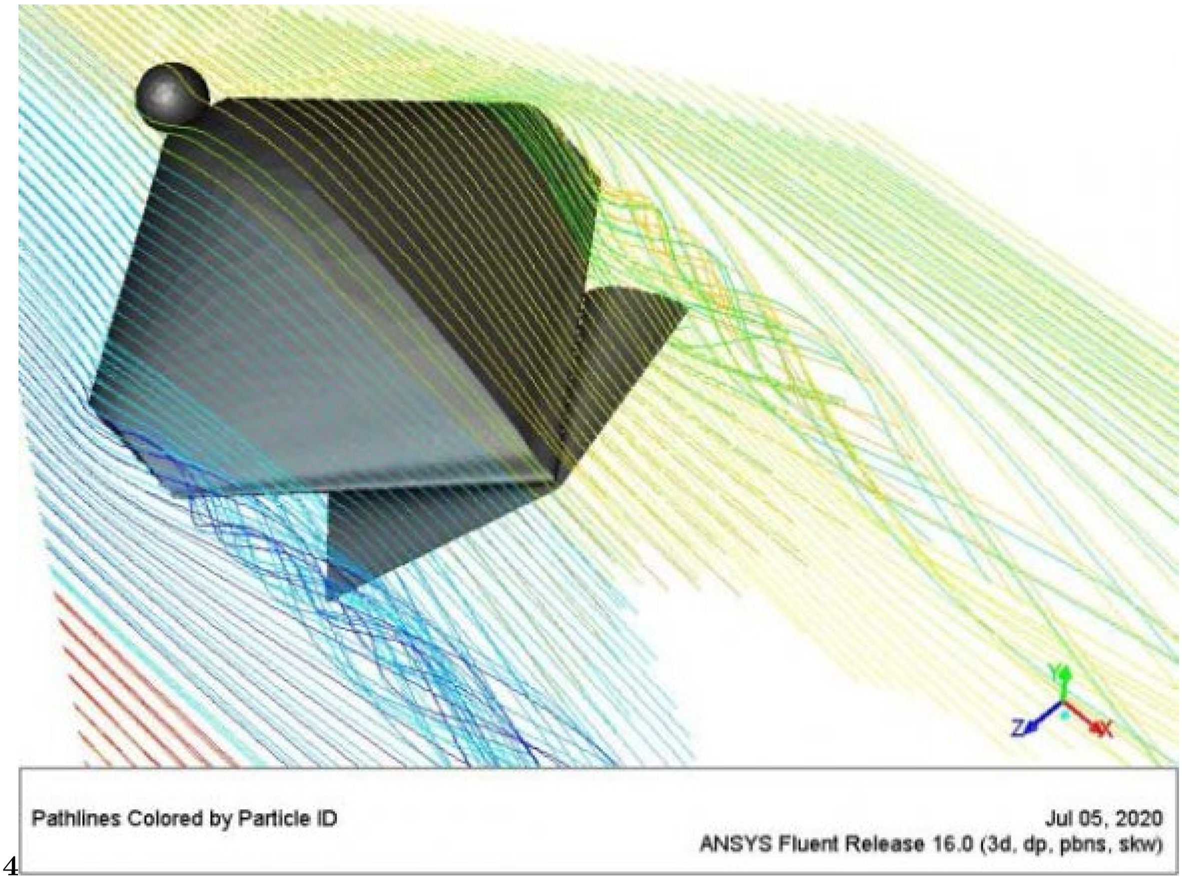


Figure 15: Figure 14 :

15

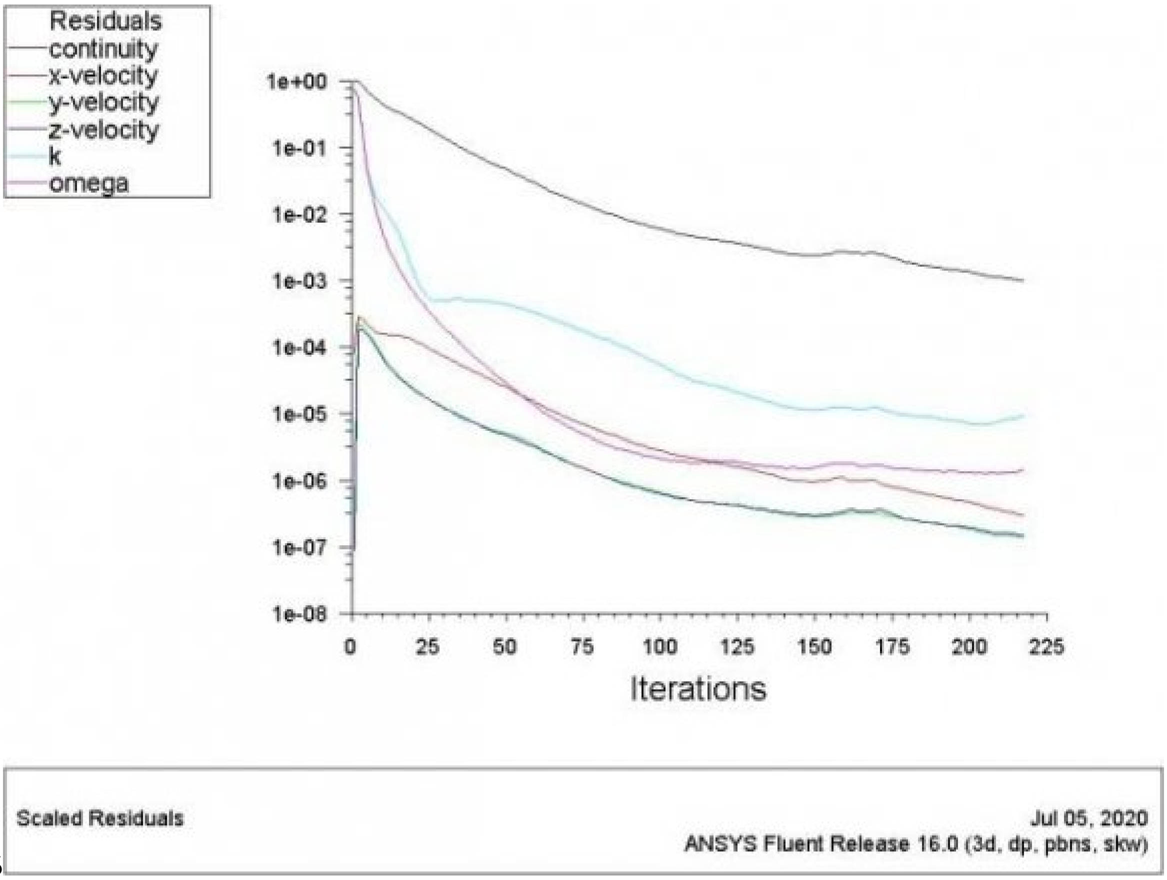


Figure 16: Figure 15 :

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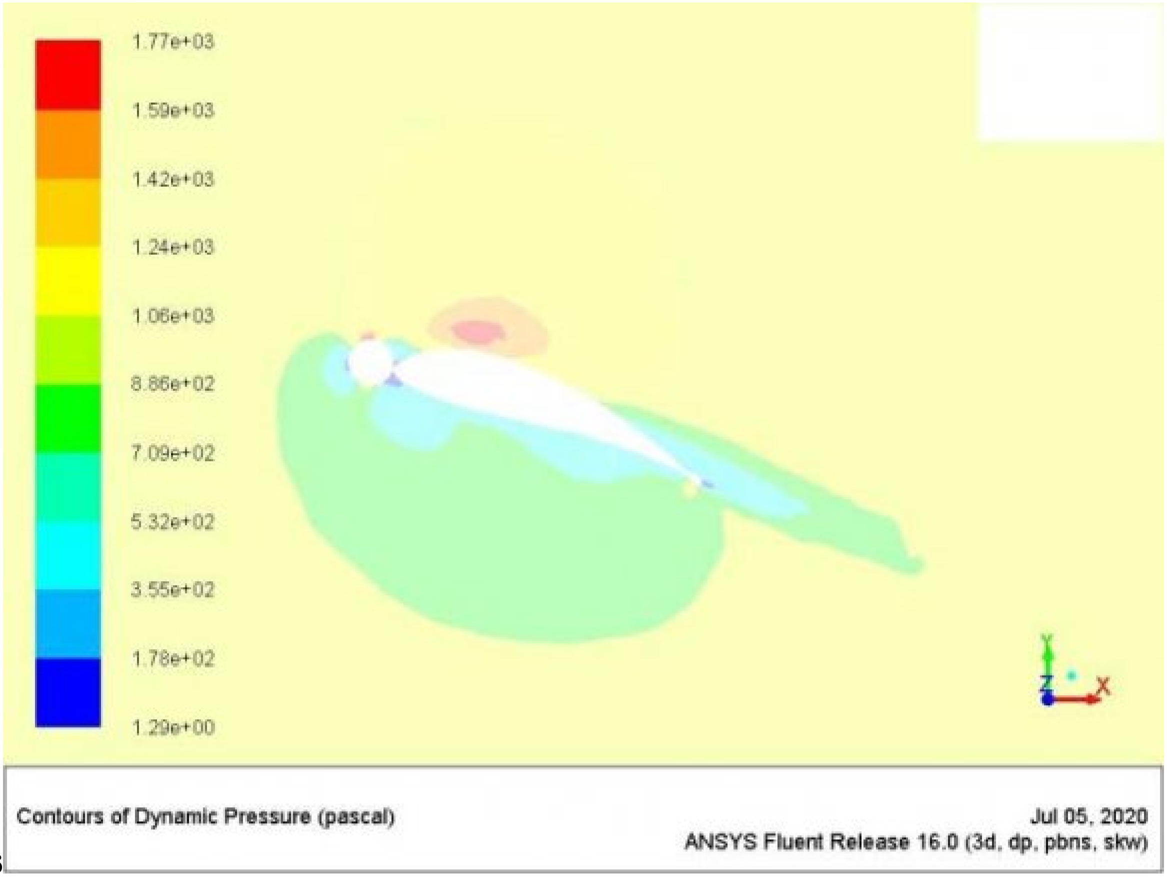


Figure 17: Figure 16 :

17

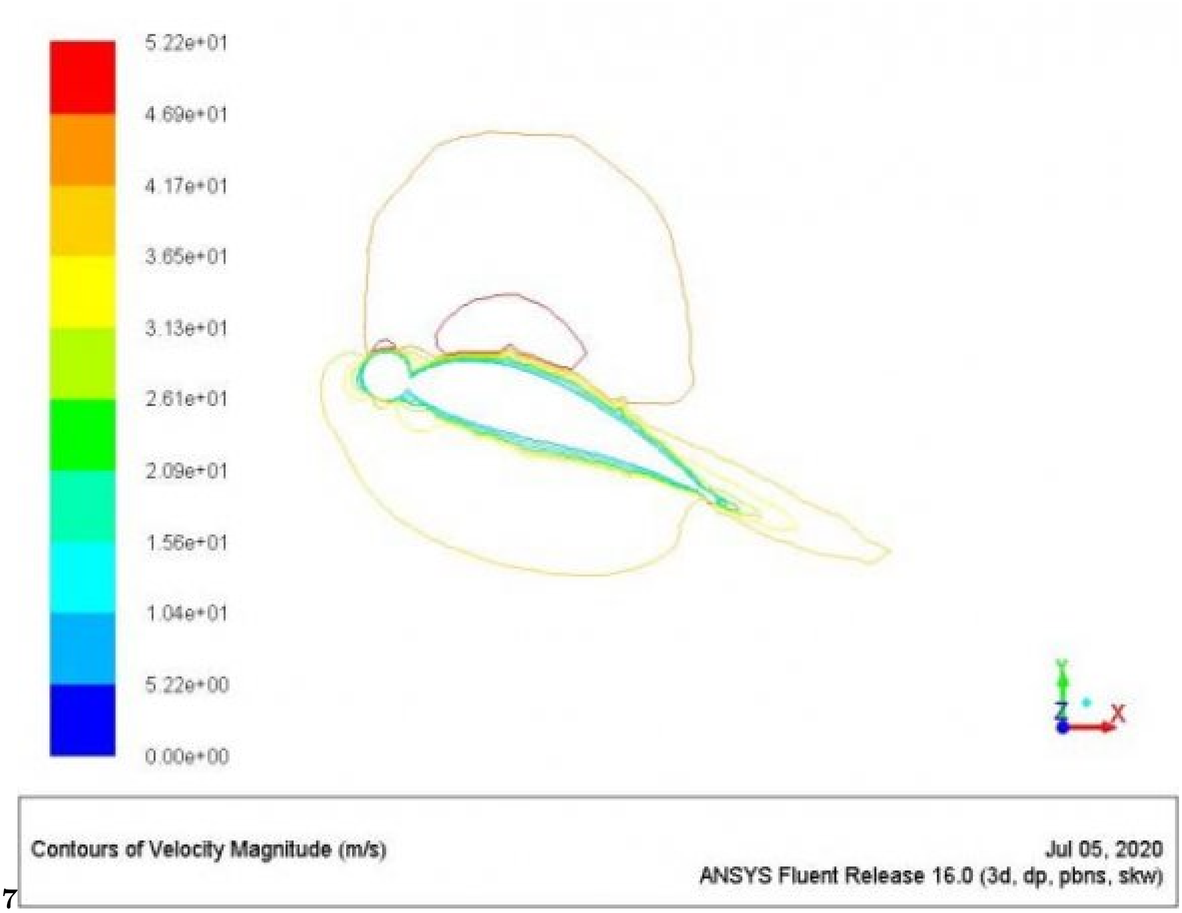


Figure 18: Figure 17 :

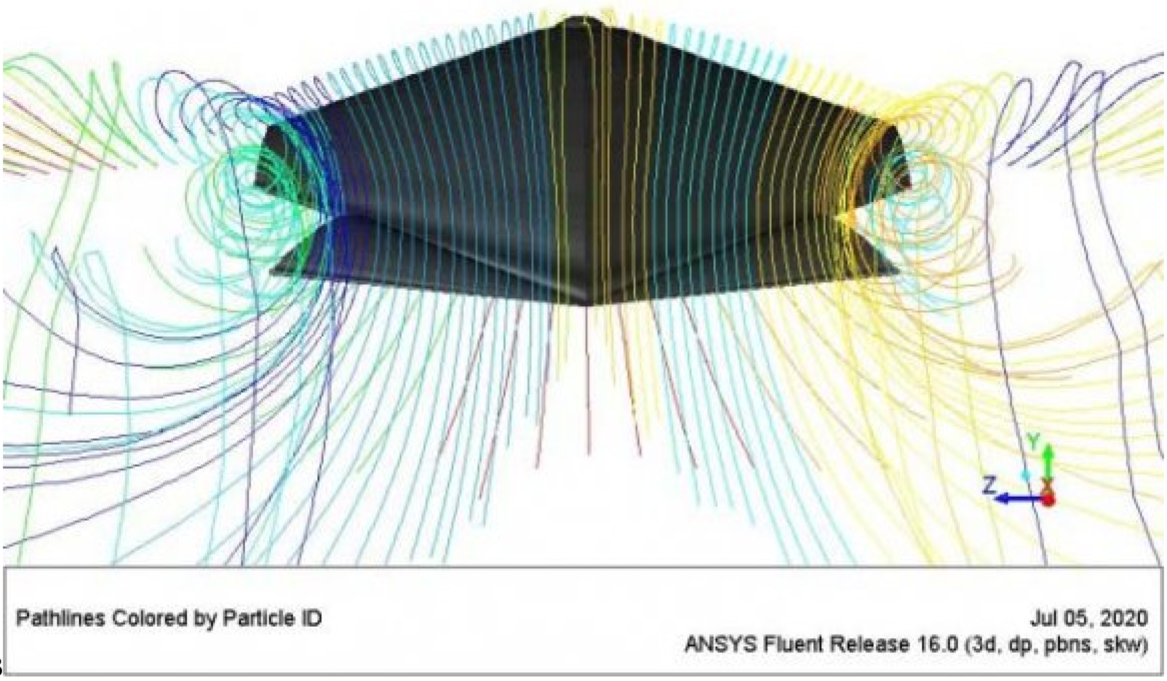
18


Figure 19: Figure 18 :

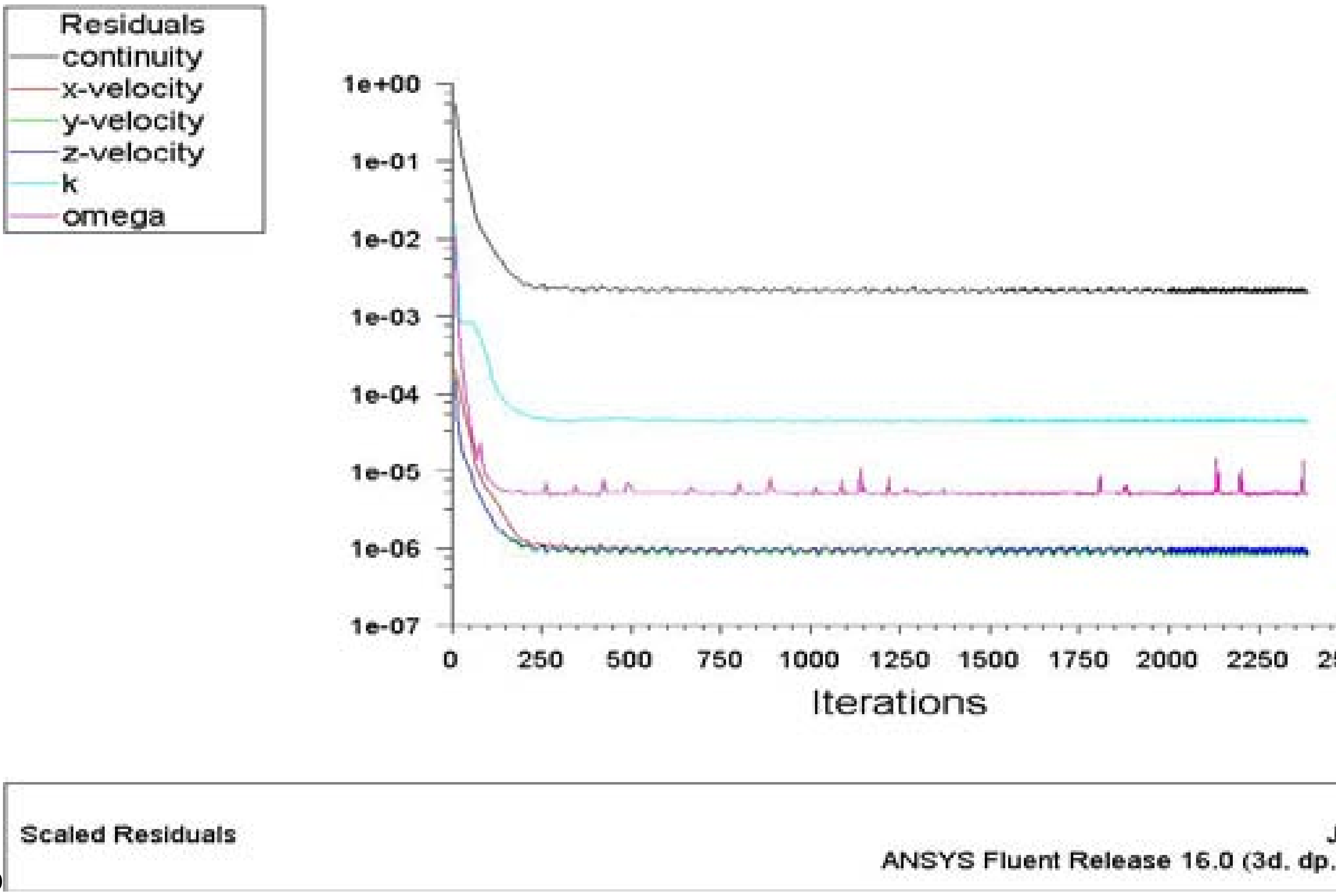


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Figure 20: Figure 19 :

1

Elements	??	?? ??	?? ??
0.1Million	6 o	1.71	0.0235
0.1 Million	6 o	1.73	0.0237
0.5 Million	12 o	2.09	0.0360
0.5 Million	12 o	2.11	0.0365

Figure 21: Table 1 :

2

Boundaries	Conditions
Inlet	Velocity Inlet
Walls	No Slip
Outlet	Outlet Pressure

Figure 22: Table 2 :

3

Wingsuit Design Type	Range (Km)	TOF (min)
Apache Wingsuit Nyberg [9]	12.466	17.63
Ansari [13]	11.27	5.38
Wingsuit Present Design	20.421	22.21

Figure 23: Table 3 :

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