Abstract — Computational fluid dynamics is a relatively young field in engineering. This method revolves around the generation of an accurate model and analyzing the accuracy of results. For acquiring accurate results through CFD, developing an accurate model is of utmost necessity. The grid dependency study of CFD shows the relation between the accuracy of grid in representing the body analyzed and results obtained.

Index Terms — Convergence, Grid Dependency, Mach number NACA Air-foil, Residual history.

I. INTRODUCTION

Computational Fluid Dynamics (CFD) is a science combining the aspects of fluid mechanics, numerical methods and programming to solve the Partial Differential Equations governing the fluid flow. The Applications of CFD are wide spread across many fields of science where the flow of the fluid appears. [3]

One of the most sensitive areas of engineering where accuracy of CFD results is of high importance is aerospace engineering. Hence improvement of accuracy in the results obtained through CFD analysis has become an essential aspect. Realizing that the accuracy primarily depends upon quality of grid network around a body, numerous grid dependency studies have been done. One of the prominent study is “Grid Dependency Study for the NASA Rotor 37 compressor blade”[5], which provided a systematic grid dependency study that quantified the amount of uncertainty that comes from grid density.

Here the analysis on NACA 0012 airfoil shall be detailed and discussed. The NACA 0012 airfoil is widely used in aerospace industry. The simple and symmetric geometry of NACA 0012 airfoil provides an excellent validation case.

To solve the fluid flow equations, a grid network around the NACA 0012 airfoil is required to simulate the flow around body. The fluid flow properties are obtained by iteratively solving the fluid flow equations. Test for a good quality grid which shall lead to an accurate solution minimizing the projection error of the solution domain will be shown.

II. PROCEDURE

CFD Analysis for an air-foil

Air-foils are classified by NACA based on the camber length, maximum thickness and the roundedness etc. into NACA 0012, NACA 0012-64 etc. There are different series of air-foils namely four digit series, five digit series and six digit series.

Here the air-foil selected for flow analysis is NACA 0012, with a thickness to chord ratio of 12%, with the camber line coinciding with the chord line. Assuming the chord length to be one unit.

a) To generate the air-foil, following equation[1] is used:

\[ y = \frac{c}{20} \times (0.2966 \times \sqrt{x} - 0.1260 \times x - 0.3516 \times x^2 + 0.2843 \times x^3 - 0.1035 \times x^4) \]

Where,
\[ t=0.12 \text{ for NACA 0012 and } x \text{ ranging from 0 and 1.} \]

b) A program is written which generates the points on the surface of the air-foil using the above equation.[2]

Air-foil is generated with 51,101,201 points on it. Figs 1 to 3 show the air-foil generated with the different number of points on its surface:
c) By using the above data the grid is generated by considering an outer boundary as a circle with radius 20 times to that of the chord length. The grid co-ordinates are obtained using Linear interpolation, Cubic spline interpolation and By solving Laplace equations.

d) For the linear interpolation and the cubic spline methods, programs were written to interpolate points between air-foil and circle by considering 31 and 51 points along the lines connecting the corresponding points of air-foil and circle. The resulting grids are plotted using a visualisation software and are shown from Figs 4 to 9 with full and s

e) Laplace equations solver developed at CFD division, DRDL is used to obtain the grid around air-foil with similar grid sizes mentioned above. Hence, the Laplace equation are solved iteratively to obtain the grids. The grid lines are clustered near air-foil due to concave shape of the inner boundary solution. Because, the Laplace equation ensures automatic clustering of points near concave shapes. This effect can be visualised from Figs 10 to 15.
After generating the necessary grids, the flow simulations are carried out for the air-foil using “Deshpande’s Kinetic Flux Vector Splitting (KFVS) Method based 2-D Euler solver” developed at CFD Division, DRDL. A local time step method is used to obtain faster convergence. The Laplacian grids are considered for the simulation with grid sizes: 51 x 31, 101 x 31, 201 x 31.[3]

Mach number (Ma): The ratio of fluid velocity to speed of sound is known as Mach number. If Ma > 1, the flow is supersonic and the flow is subsonic if Ma < 1.

### III. RESULTS

i. The two flow conditions namely transonic flow with \( M = 0.85 \) & \( \alpha = 1 \) and supersonic flow with \( Ma = 2.0 \) & \( \alpha = 5 \) are considered for flow simulation.

ii. The results are plotted for each case on every grid in terms of pressure contours as shown in Figs 16, 18, 20, 22, 24 & 26. The sufficient convergence were obtained which can be seen from Figs 17, 19, 21, 23, 25 & 27.
iii. The first test case (Ma=0.85, α=1) consists of a shock on top surface and another shock on bottom surface of the air-foil which are nicely captured in CFD simulation (Fig. 16).

iv. The second test case (Ma=2.00, α=5) consists of a detached shock in front of the leading edge of the air-foil also captured nicely in the CFD simulation (Fig. 18).

v. Increase in number of points of the grid improved the accuracy which can be seen from Figs 16 to 27.

Fig 16: Pressure contours on NACA 0012 airfoil for Ma=0.85 & α=1 (Grid: 51 x 31)

Fig 17: Residual history after 15,000 iterations (Grid: 51 x 31)

Fig 18: Pressure contours on NACA 0012 airfoil for Ma=2, α=5 (Grid: 51 x 31)

Fig 19: Residual history after 5,000 iterations (Grid: 51 x 31)

Fig 20: Pressure contours on NACA 0012 airfoil for Ma=0.85, α=1 (Grid: 101 x 31)

Fig 21: Residual history after 15,000 iterations (Grid: 101 x 31)
Fig 22: Pressure contours on NACA 0012 airfoil for \( M_a=2, \alpha=5 \) (Grid: 101 x 31)

Fig 23: Residual history after 5,000 iteration (Grid: 101 x 31)

Fig 24: Pressure contours on NACA 0012 airfoil for \( M_a=0.85, \alpha=1 \) (Grid: 201 x 31)

Fig 25: Residual history after 15,000 iterations (Grid: 201 x 31)

Fig 26: Pressure contours on NACA 0012 airfoil for \( M_a=2, \alpha=5 \) (Grid: 201 x 31)

Fig 27: Residual history after 5,000 iterations (Grid: 201 x 31)
vi. The lift and drag coefficients are presented in Table-1 for these two cases on different grids and the effect of grid size can be clearly seen.

<table>
<thead>
<tr>
<th>Flow Condition</th>
<th>Grids</th>
<th>Lift co-eff. $C_L$</th>
<th>Drag co-eff. $C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach 0.85 = 1°</td>
<td>51 x 31</td>
<td>0.3105</td>
<td>0.0922</td>
</tr>
<tr>
<td></td>
<td>101 x 31</td>
<td>0.2698</td>
<td>0.0837</td>
</tr>
<tr>
<td></td>
<td>201 x 31</td>
<td>0.252</td>
<td>0.0755</td>
</tr>
<tr>
<td>Mach 0.85 = 5°</td>
<td>51 x 31</td>
<td>1.0620</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td>101 x 31</td>
<td>1.0260</td>
<td>0.768</td>
</tr>
<tr>
<td></td>
<td>201 x 31</td>
<td>1.0496</td>
<td>0.7351</td>
</tr>
</tbody>
</table>

**IV. CONCLUSION**

The effect of grids on the flow and aerodynamic coefficients are studied using a 2-D Euler Solver. The necessity of more points and clustering of points near body is emphasized to increase the accuracy of the flow. It is also seen that the solution for supersonic flow condition converges faster when compared to transonic case. The accuracy of the flow can be further improved if more points are clustered near the airfoil.

**V. FUTURE ENHANCEMENT**

With keen insights obtained from the grid dependency study of NACA 0012, development of optimum sized grid can be applied to several other aerodynamic structures.

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**PERSONAL PROFILE**

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I am currently working at a premiere engineering software development organization Hexagon AB as Software analyst. I graduated from Gokaraju Rangaraju Institute of Engineering and Technology in Civil Engineering. My interests are structural design in aerospace engineering, structural dynamics and computational mechanics. My inquisitiveness and thirst for knowledge has enabled me complete a total of 3 projects and an internship. I am currently working independently on wing design project for an aircraft. I was a member of IEEE and ICI for 2 years and served in several office bearer positions.