PERFORMANCE ANALYSIS OF TRANSONIC PROPELLER

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Abstract - *A transonic propeller is designed and modified to obtain high performance and efficiency at transonic conditions. The Eppler 387 airfoil is used for each constant section propeller design from Advanced Ducted Propfan Analysis Code (ADPAC). It is chosen since it has good performance at low Reynolds number. A three dimensional model for the design was designed using SolidWorks. Incorporating data from the ADPAC for twist and chord length, E387 was designed, where the tip section is being modified with Eppler 374 and Eppler 397. The design variation includes change in twist angle and chord for Mach number ranging from 0.45 to 0.6. The transonic flow over propeller is analyzed using Ansys Fluent Academic Version 2020 R1. The thrust, power, and torque coefficient are calculated from the analysis for varying advance ratios from J= 0.8 to 1.8. Also the study of tip shock is done to improve the overall efficiency of the propeller.*

Key Words: **Transonic Flow, Tip Shock, Performance, Flow analysis.**

1 NTRODUCTION

1.1 Introduction to Propeller

The ancient Greek scientist Archimedes in 200BC developed the rotating screw design which is used in the first version of the propeller design. In earlier days these screws are used by ancient civilization to lift water from wells with much less effort. Leonardo da Vinci in the mid-1400s reimagines the screw concept for a flying machine. In the mid-1700s, the rotating screw design was used by the inventors to propel boats and ships in water. In 1783, inventors began to experiment with methods of propelling. Numerous heavier than air flying machines were designed and built using propellers based on the screw shaped design over the next few decades. In early 1900s the first successful airplane propeller was designed by Wright Brothers. The first propeller was made of wood.

1.2 Principle of Propeller

Propeller is an aerodynamic device which converts rotating energy into propulsive force creating thrust. Generally, through some applications of Newton's Third law, the different types of propulsion systems develops thrust in different ways. Propeller have two or more blades spaced evenly around the hub and are in fixed or variable pitch.

The propellers majorly used in aviation industry are

- Fixed pitch propeller
- Ground adjustable propeller
- Constant speed propeller
- Feathering propeller
- Reverse pitch propeller
- Controllable pitch propeller
- Contra rotating propeller

1.3 Properties of Propeller

The propeller can be subjected to aerodynamic issues such as angle of attack, stall, drag and transonic airflow. The speed and thrust produced in propeller are given by the following parameters.

- The speed of engine is directly related to the rotational speed and mechanically linked to the engine in propellers
- The amount of thrust produced by the blade is proportional to the blade area.
- The relative airspeed at any point on a propeller is vector sum of the tangential rotational speed of the propeller and aircraft speed.
- The transonic speed is achieved by longer blades at lower RPM than shorter ones.
- The propeller characteristic should match the engine characteristic.

To create thrust the propellers need to be supplied with power for you we need an engine, which can be piston engine or gas turbine engine or any other device that produce power.

1.4 Propeller Blade Structure

Mostly, the propellers are made up of three or more blades. These blades are made up of airfoil sections, which put together, create the blade shape, these blades when in rotation, in a predetermined manner, helps in producing thrust.

- The blade elements are made up of airfoil shapes of known lift, C_l and drag, C_d characteristics.
- In practice a larger number of different airfoils are used to make up on propeller blade.
- Each of the blade elements have their own lift, Cl and drag, C_d coefficient characteristics.

The airfoil shapes can actually vary from root to tip of the blade. So, along the length of the blade, the airfoil shapes can vary quite really a lot. As a result of which C_l and C_d characteristics would also vary substantially from the root of the blade to the tip of the blade.

The section or blade element is an airfoil comparable to a cross-section of an aircraft wing. The upper surface of an aircraft wing is said to be similar to the blade back in the cambered or curved side of the blade. In propeller blade, the flat side is said to be blade face. The chord line is an imaginary line drawn through the blade from the leading edge to the trailing edge. As the propeller rotates, the leading edge is the thick edge were air strikes first.

1.5 Propeller Performance

The propeller is represented by a simple classical propeller momentum theory. The theory is based on the assumption of a stream tube, extending from infinitely far upstream to infinitely far downstream, exactly enclosing the propeller disk. In the propeller flow is assumed to be inviscid and incompressible, and it is said that the rotation of the fluid is neglected, it is assumed that the axial velocity and pressure is uniform at each cross section of the stream tube.

The propulsive power P_P of a propeller is defined as the propulsive thrust T_p multiplied by the undisturbed air speed V∞. It is the rate at which useful work is done. The propulsive efficiency η_P is defined as the ratio of the propulsive power to the shaft power P_s, the power required to turn the propeller. These often used quantities describing propeller performance are the thrust coefficient C_T, power coefficient C_p, torque coefficient C_Q and the advance ratio J is defined as

$$C_T = \frac{T_P}{\rho_\infty n^2 D_P^4}$$

$$C_Q = \frac{Q}{\rho_\infty n^2 D_p^5}$$

$$C_P = \frac{B\tau_{blade}\,\omega}{0.5\rho A V_{rated}^3}$$

$$J = \frac{V_\infty}{nD_P}$$

Where ρ_∞ is the undisturbed air density, η the propeller rotational speed and D_p the propeller diameter. In case of classical momentum theory, it is evidently derived that propulsive efficiency also knows as ideal efficiency is only valid if the flow is inviscid and incompressible flow which is equal to

$$\eta_p = \frac{J*C_T}{C_P}$$

1.6 Forces acting on a propeller

1. Thrust is the air force on the propeller which is parallel to the direction of advance and induced bending stress in the propeller.
2. The blade is thrown out from the center by the centrifugal force that caused the rotation of the propeller.
3. Torsion or Twisting forces in the blade itself, caused by the resultant of air forces which tend to twist the blade toward a lower blade angle.

1.7 Stress acting on a propeller

1. Bending stresses are induced by the thrust forces. When the airplane is said to move through the air by the propeller the stresses tent to bend the blade forward.
2. Centrifugal force is caused due to tensile stresses.
3. By two twisting moments the torsion stresses are produced in rotating propeller blades. The aerodynamic twisting moment is defined as if one of these stresses is caused by the air reaction on the blades. The another stress is caused by centrifugal force and is called the centrifugal twisting moment.

2.1 Selection of Airfoil

Koch [2] tested the performance of the two, three and four bladed propeller of E387. Based on his analysis it was found that three bladed propeller was more efficient than the rest of the two, due the decrease in disc loading and manufacturing feasibility. According to Koch, the performance of the propeller is always best if the laminar boundary layer transition takes place to turbulent boundary layer before reaching pressure gradient. If the energy is increased which will result in withstanding of adverse pressure gradient ultimately good lift and drag characteristics. Preliminary studies show that altitude of 25.9 km (80,000ft) free-stream Mach number could range from 0.4 to 0.8. ADPAC three dimensional design point data have been carried out in the inlet Mach 0.45. The Eppler 387 airfoil has been tested in various facilities including Langley Low-Turbulence Pressure Tunnel and validated numerous airfoil and analysis code. Adkins and Liebeck [1] made several iterative design procedure to estimate hub and tip radii, number of blades, chord length distribution which are varied along the blades and does not exceed 80% of the maximum experimental lift coefficient. Given below is the graphs plotted between chord and twist angle vs the radial length of thepropeller , prefered by Koch[2]. For designing the appropriate propeller, chord length and twist angle has to be determined, which has been plotted through Web Plot Digitiger.

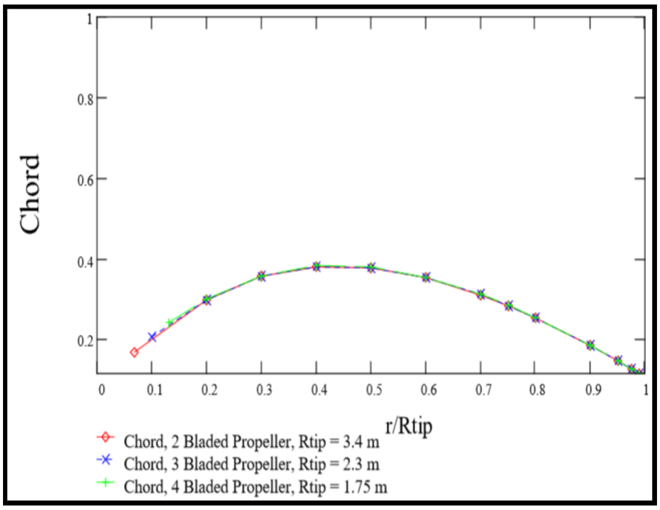

Fig 2.1 Chord vs Radial Length, Koch(1998)

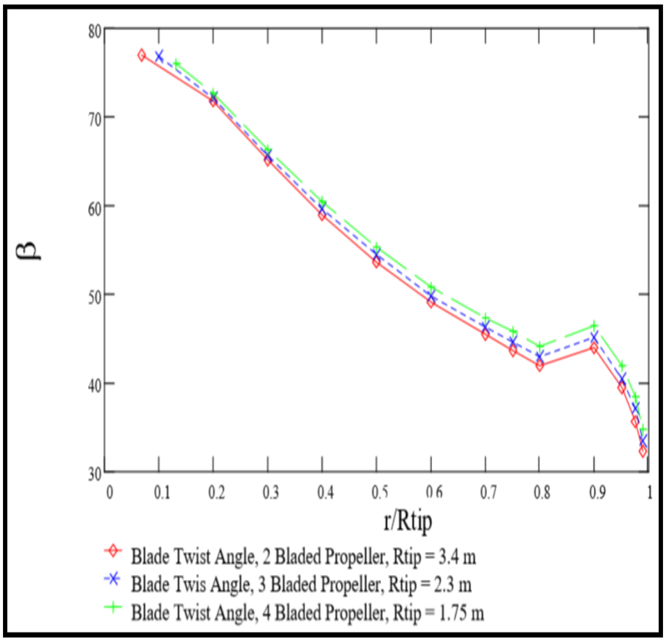

Fig 2.2 Twist Angle vs Radial Length, Koch(1998)

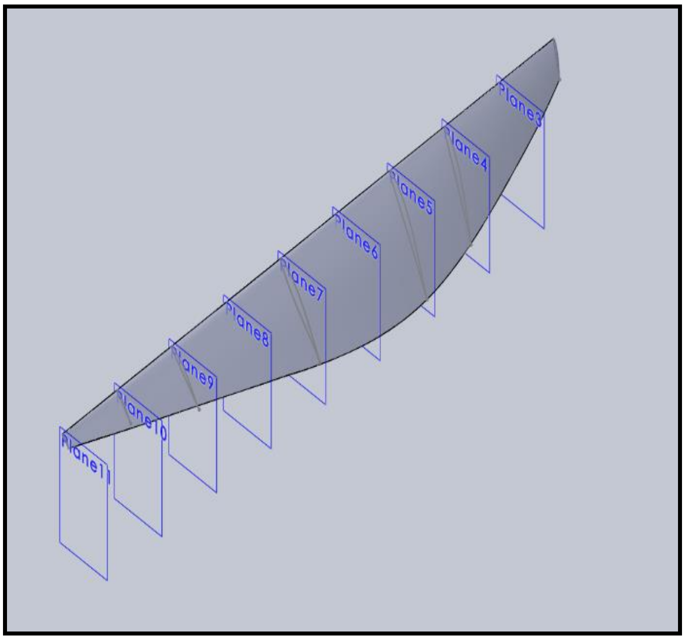

Figure 2.3 Section View of CAD Model

3.1 Modelling of Propeller

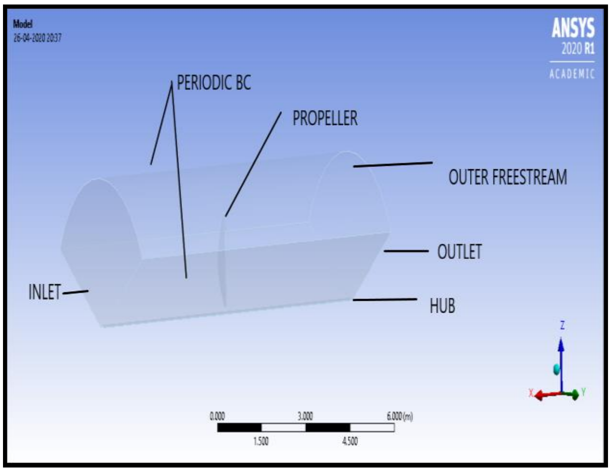

Figure 3.1 Description of Domain

3.2 Meshing

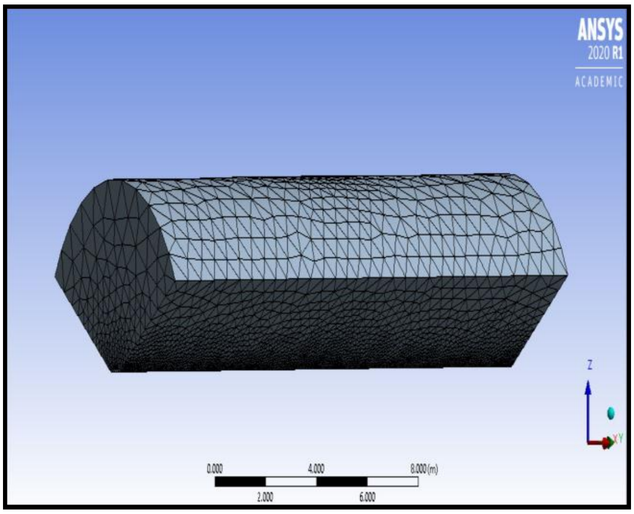

Figure 3.2 Domain Mesh

Meshing is done using ANSYS workbench where two types of mesh is implemented. Meshing by algorithm and meshing with elements are simultaneously done to enhance the meshing and tolerance level. Patch Confirming method is being used to mesh all the faces, edges, vertices within very tolerance level.

Different domain geometry demands different kind of meshing function, edge sizing has to be carefully done on the edges of the airfoil blades to capture the curvature of the propeller. Inflation is a type of scalable wall function which determines the thickness of the first layer of the mesh to capture the flow properties. A maximum number of layer ensures, predicting good values near the wall. Tetrahedral elements constitute most of the interior in the domain, whereas triangular elements in the wall section.

Table 3.2 Mesh properties

VARIABLES	VALUE
Mesh Classification: -Global Mesh Control	Unstructured
Element Type -Volume -Wall	 Tetrahedral Triangle
Growth Rate	1.2
Local Mesh Control -Match control	 Cyclic Transformation
Face Sizing -Element Size	 0.1m
Edge Sizing - Divisions	 80
Inflation -No. of layers -First layer height	 12 8.e-005m
Advanced Size Function	Proximity and Curvature
Relevance Centre	Fine
Curvature Angle	18°
Number of Nodes	88353
Number of Elements	368707
Orthogonal Quality -Minimum -Average	 1.15e-003 0.67
Aspect Ratio -Minimum -Average	 1.161 35.627

3.3 Boundary conditions

Table 3.3 Boundary conditions

Face Value	Type of Boundary Condition
Inlet Face	Velocity Inlet 154.35 m/s
Temperature	293 k
Rotating domain	Frame Motion 1120 rpm
Propeller blade	No slip wall
Hub	Slip wall
Side(2x)	Periodic Boundary Condition
Freestream	Symmetry Boundary Condition
Outlet	Pressure Outlet

4.1 Grid Independence Study

The grid independence test is carried out in order to ensure that the output obtained is independent of the element size and nodes generated in the meshing of the constructed geometry. The meshing details for the independent study are shown below in the table.

Table 4.1 - Data of Grid Independence Study

Element size(mm)	Number of elements	Coefficient of power(C_P)	Coefficient of thrust(C_T)	Coefficient of torque(C_Q)
1.56	284996	0.869	0.126	0.0258
1.3	341279	0.871	0.125	0.0260
1.12	368707	0.866	0.127	0.0258
0.9	445425	0.869	0.123	0.0259

The data shows that change in the element size from 0.9mm to 1.56mm creates a change in the flow parameters as it shows the error corresponding to the number of nodes present. And the data also shows the variation in the coefficient of power, thrust and torque.

The graphical representation of the data is shown below which depicts that with increasing the number of nodes values doesn't change drastically.

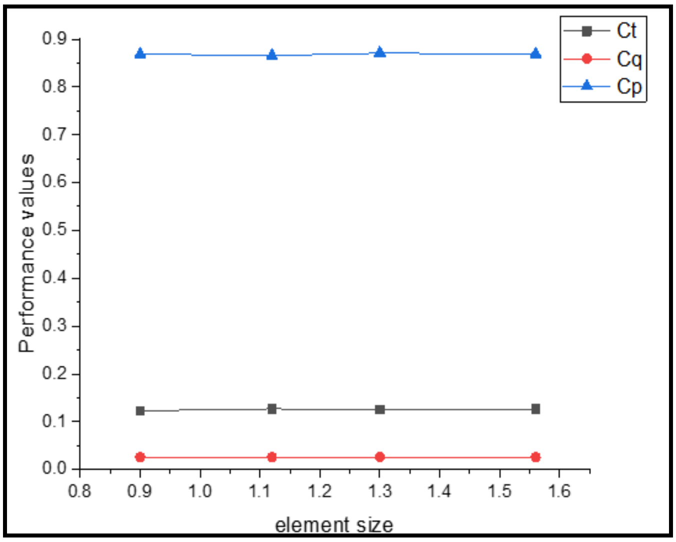

Figure 4.2 Performance Vs Element Size

Thus, the grid independent test reveals that the element size of the sizing plays a major role in generating results without error. The element size chosen for the meshing of all the different geometry created is 0.9mm. The meshing nodes generated in all the geometry is greater than 340000.

Summary

In this manner, the propeller blade is modelled and the geometry coordinates is imported for constructing a solid surfaced propeller blade. The meshing of the geometry is thus carried out with the help of grid independent test at an element size 0.9mm generating fine mesh geometry for the fluent.

5.1 RESULTS AND DISCUSSION

From the analysis of Koch, it is clear that E387 is not suitable airfoil at the tip section for transonic speed therefore, in the present work tip section of the propeller is modified with E374 and E397. Ansys Fluent is used for various operating condition for varying advance ratio 0.8 to 1.8, to check the performance parameter and study of tip shock at transonic flow conditions.

5.1 PERFORMANCE CALCULATION

Prediction of airfoil performance data is being plotted using CFD, with different advance ratio. For a constant propeller blade angle, advance ratio has an adverse effect on the considerable flow and other parameters. For three different kind of propeller, we took four different advance ratios from 0.8 to 1.8. Where we can see a considerable change in the performance parameter. As the value of advance ratio increases, the value of cp, ct, cq, gradually decreases and the efficiency increases. Advance ratios are generally varied by changing the rotational speed of the propeller. From the ADPAC 3-D results we were able to find out design point of values at the optimum advance ratio J=1.8. Experimental data is available only for 2-D ADPAC validated with strip theory as mention in [1]. The results are displayed in below graph which clearly shows that E387 has considerably low performance as compared to other two modified propellers. These figures, make it clear that at low value of advance ratio there is no considerable efficiency in the propeller.

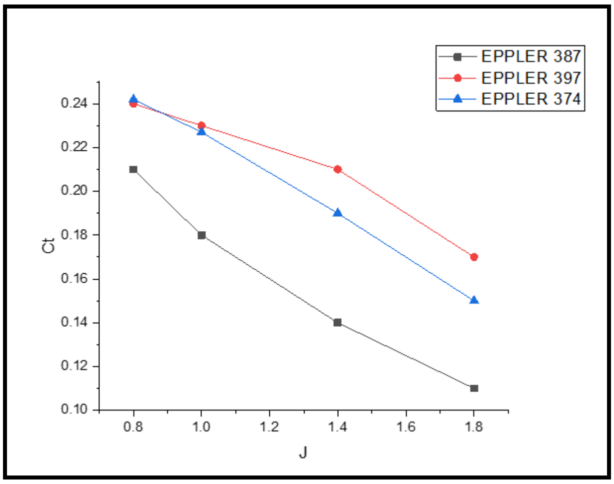

Figure 5.1a) Coefficient of Thrust vs Advance Ratio

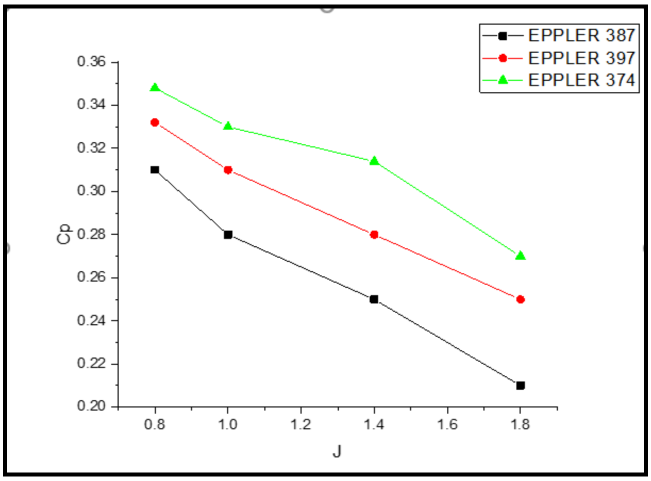

Figure 5.1 b) Coefficient of Power vs Advance Ratio

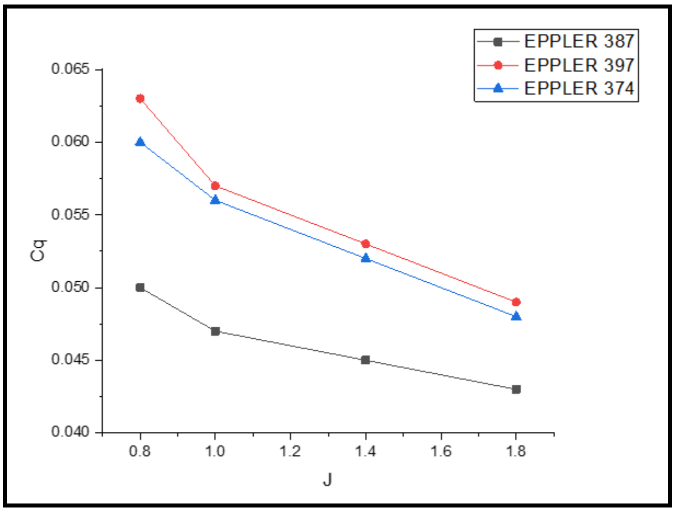

Figure 5.1 c) Coefficient of Torque vs Advance Ratio

In the graph ct vs J , initially in the lower advance ratio the ct of Eppler 397 is below than the Eppler 374 , whereas Eppler 387 has very low ct as compared to other. This is due to the fact that angle of attack of airfoil at the tip section is higher as compared to the root section of the propeller. In modified propeller of E397 and E374, the tip angle of attack is 5˚ higher as compared to E387. The twist angle plays a key role in production of shock wave, which adversely increase the drag and reduce the performance of the propeller. In E397 there is considerable increase in ct, cp, as the advance ratio move, but after J= 1.4 the values drop, ultimately leading in increase of efficiency.

PROPELLER EFFECIENCY

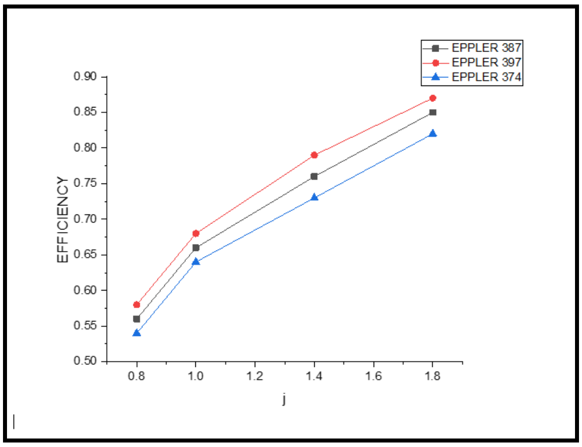

Figure 5.1 d) Efficiency Vs Advance Ratio

Propeller efficiency is used to predict the performance of the propeller mounted aircraft, as it is an important criterion for the designer to predict the reasonable level of accuracy in the overall design parameter. Blade element theory is used to predict the efficiency of the propeller, which leads to inconsistent results as it suggests the efficiency of the propeller reaches 100% when the viscous force is made zero. But in momentum theory approach as inviscid where a realistic efficiency is attained. In comparing three different modified propeller E397, has an increased efficiency of 2%.

To evaluate the transonic flow conditions over the tip of propeller for airfoil E397 has been carried out using Ansys Fluent, where the operating rpm was 3000, with inlet Mach=0.6 at the altitude of 80,000 feet.

5.2 Velocity Contour

The velocity contours are a visual representation of the method of measuring the stream discharge in which point velocity measurements are translated into average cross-sectional flow velocities by contouring the point velocities; these averages are then multiplied by the areas of the cross sections to give the discharge.

The velocity contours here are created by inserting a reference plane from the ZX plane and slicing the contours with respect to it in order to obtain the velocity contours. The properties of the flow around the propeller can be simultaneously evaluated with either stationary or moving reference frame moving with an angular velocity. Below in Fig. 5.2, velocity contour is expressed with respect to moving reference frame formulation where it is measured by non-inertial observer moving together with the blade at the same angular velocity. In both the graphical contour it is visible that the tip velocity leaving the airfoil it is in the range of 1.5 times of the incoming freestream velocity, which makes the flow condition to be at transonic speed. There is the formation of oblique shoch wake from the leading edge of the airfoil tip on the suction side of the propeller, where the pressure side of the propeller the velocity increases along the chord of the propeller airfoil. Due to added energy of the moving object, the total flow properties such as pressure, density, temperature have different values. As the angle of attack decreases along the radial length of the propeller, there in significant reattachment of flows to the propeller. The transonic flow starts at the downstream of the propeller in mid-way

E397

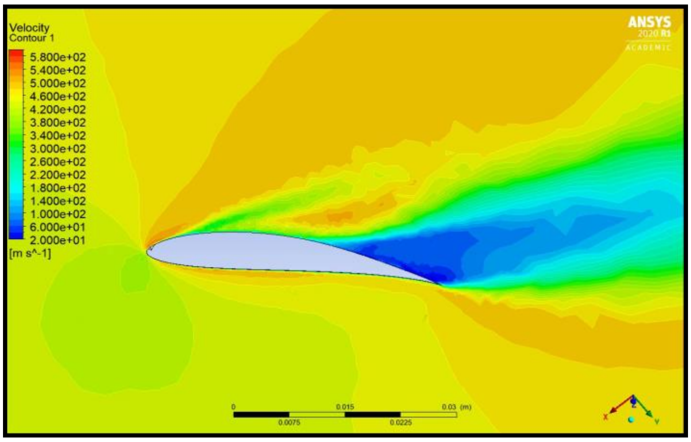

Figure 5.2 a) Velocity contour at the tip Eppler 397

E397

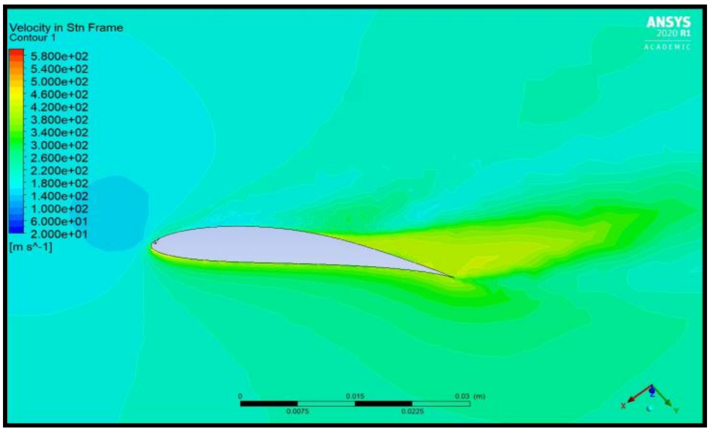

Figure 5.2 b) Velocity Contour for Stationary Frame at the tip airfoil Eppler 397

5.3 Pressure Contour

Pressure contour determine the variation of pressure along the propeller blade and the pressure variation along the tip airfoil section. At transonic flow condition, there occurs a numerous unsteady phenomenon such as interaction of shock wave with a separate boundary layer. There occurs a pressure fluctuations and lead to form shock waves. As mentioned in the ADPAC, there occurs a tremendous shock at the tip at adverse pressure gradient, which induce high drag and reduce the performance of the propeller.

E397

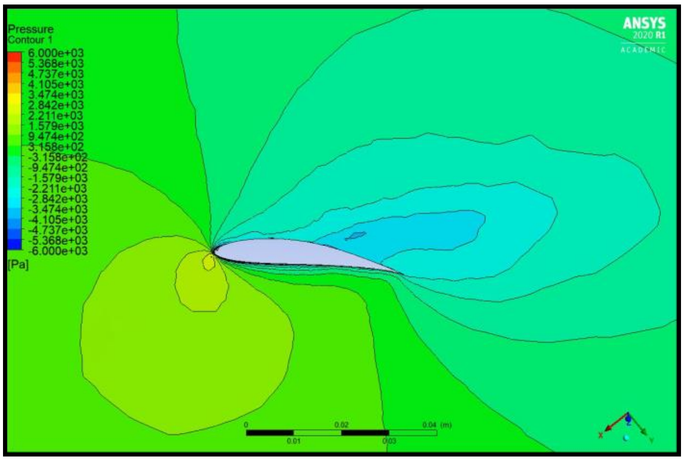

Figure 5.3 a) Pressure contour at the tip airfoil for Eppler 397

Pressure distribution around the airfoil determines the force distribution on the model, due to shadow regions on different planes the highest flow occurs in the shadow region leading to pressure variation. E397 has a smooth curve till the leading edge, where the suction decreases. As the relative velocity decreases on the suction side of the propeller there is significant recovery in the pressure.

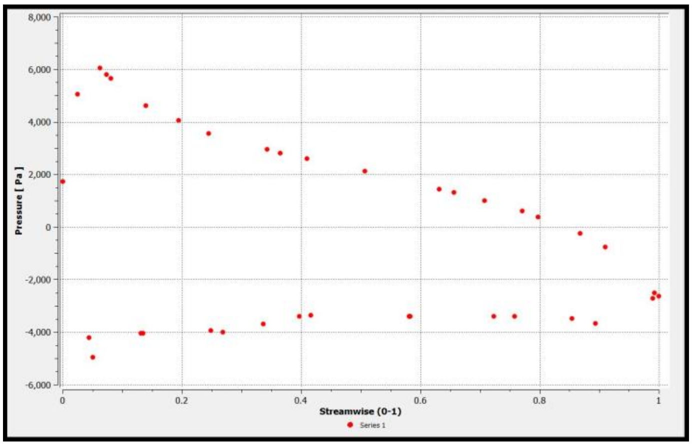

Figure 5.3 b) Pressure Distribution for tip airfoil Eppler 397

It is considerably seen that there is significant pressure drop on the suction side and formation of shock wave and reattachment of flow occurs. E397, twist angle have been modified to acceptable angle of 5˚, thereby increasing the angle of attack slightly to overcome the shock. Shock wave position can have been seen in leading edge of the propeller as increasing the incidence angle increase the local Mach number at the fixed point upstream, thereby small bubble in the shock dies out before reaching the trailing edge.

6. CONCLUSIONS

High altitude propeller are complex designs which demand high efficiency to operate at transonic tip speed. For good characteristic of efficiency, propeller design and geometry plays a vital role. Thesis conducted by Koch [2], compared and validated the performance of E387 with strip theory method as mentioned in Adkins[1]. From the analysis of Koch it is clear that E387 is not a suitable propeller as it produces enormous shock at least at the tip section of the propeller. Increase in shock would lead to increase in adverse drag which ultimately reduces the performance of the propeller. So our work mainly focused to improve the tip section of the airfoil by partially modifying, only the tip section with airfoil Eppler 374 and Eppler 397. From the initial analysis of performance with variation in advance ratio it is determined that optimum condition of efficiency would be at the advance ratio of J=1.8, and there is increase in efficiency of 2% in case of modified Eppler 387 with tip section Eppler 397. Shock study analysis is also done on the tip section of the propeller, with the change in twist angle at the tip of the airfoil, we were able to get a reduced shock wave as compared to other tip airfoils. With the increased twist angle the flow gets reattached to the surface, even though there is formation of oblique shock wave.

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