6.1 Introduction

The gurney flap (wicker bill) was a small flat tab projecting from the trailing edge of a wing. Typically it is set at a right angle to the pressure side surface of the airfoil, and projects 1 % to 2 % of the wing chord. This trailing edge device can improve the performance of a simple airfoil to nearly the same level as a complex high-performance design. This device operates by increasing pressure on the pressure side and decreasing pressure on the suction side. And this device is helping the boundary layer flow stay attached all the way to the trailing edge on the suction side of the airfoil. Common applications occur in auto racing, helicopter horizontal stabilizers, and aircraft where high lift is essential, such as banner-towing airplanes (Hossain et al., 2007).

The gurney flap increases the maximum lift coefficient ($C_{L,max}$), decreases the angle of attack for zero lift ($\alpha_0$), and increases the nose down pitching moment ($C_M$), which was consistent with an increase in camber of the airfoil. It also typically increases the drag coefficient ($C_d$), especially at low angles of attack. Although for thick airfoils, a reduction in drag is reported. A net benefit in overall lift to drag ratio is possible if the flap is sized appropriately based on the boundary layer thickness. The gurney flap increases lift by altering the Kutta condition at the trailing edge (Bechert et al., 2000).
The wake behind the flap is a pair of counter-rotating vortices that are alternately shed in a von Karman vortex street. In addition to these span wise vortices shed behind the flap, chord wise vortices shed in front of the flap and become important at high angles of attack. The increased pressure on the lower surface ahead of the flap means the upper surface suction can be reduced while producing the same lift (Mark and Gotz, 2008).

The term "winglet" was previously used to describe an additional lifting surface on an aircraft, e.g., a short section between wheels on fixed undercarriage, but today it refers to a near-vertical extension of the wing tips. The upward angle of the winglet and its inward or outward angle as well as its size and shape are critical for correct performance and were unique in each application (Hantrais and Grenon, 2009).

The wingtip vortex which rotates around from below the wing strikes the cambered surface of the winglet generating a force that angles inward and slightly forward, analogous to a sailboat sailing close hauled. The winglet converts some of the otherwise-wasted energy in the wingtip vortex to an apparent thrust. This small contribution can be worthwhile over the aircraft’s lifetime, provided the benefit offsets the cost of installing and maintaining the winglets. Another potential benefit of winglets was that they reduce the strength of wingtip vortices, which trail behind the plane. When other aircrafts pass through these vortices, the turbulent air can cause loss of control, possibly resulting in an accident (Smith et al., 2001).

6.2 Studies on Gurney Flaps and Winglets

Cory et al., (1998) performed two-dimensional numerical investigation to determine the effect of a gurney flap on a NACA 4412 airfoil. A flat plate gurney flap with the order of 1 to 3% of the airfoil chord in length was oriented
perpendicular to the chord line and located on the airfoil windward side at the trailing edge. Gurney flap sizes of 0.5 %, 1.0 %, 1.25 %, 1.5 %, 2.0 %, and 3.0 % of the airfoil chord were studied. Computational results were compared with experimental results. In this the numerical solutions show that some gurney flaps increase the airfoil lift coefficient with only a slight increase in drag coefficient. Gurney flap sizes less than 1.25 % of the main airfoil chord will result in an increased lift coefficient, with very little increase in drag. In fact, at higher lift coefficients the drag is lower than that of the clean airfoil configuration Jany et al., (1998) showed that the use of the gurney flap increases the loading along the entire length of the airfoil, with a large increase in trailing-edge loading.

A wind tunnel experiment was conducted by Ferrer and Munduate (2007) in order to investigate the influence of a gurney flap upon the aerodynamic behavior of an HQ 17 airfoil. The airfoils, with and without the gurney flap, were submitted to two different turbulent flows with the same mean wind velocity but with different turbulence structures. Lift and drag coefficients were calculated in both the cases. The results in this paper show that the gurney flap acts enhancing the lift coefficient of the airfoil and the performance it was almost independent of the scales of the incoming turbulence. The tests were performed at turbulence intensity of 1.8% and 3.5% and at a Reynolds number of 3x10^5.

Inam et al., (2007) describes the potential of winglets for the reduction of induced drag without increasing the span of the aircraft. For this experiment a model aircraft whose wings profile was NACA 4315 with three different types of winglet (rectangular, triangular and circular) were constructed for experiment. Aerodynamic characteristic of the model aircraft wing with rectangular, triangular and circular winglets and without winglet was studied
using a subsonic wind tunnel. The experimental results show that the drag decreases by 26.4 % from 30.9 % as compared to the aircraft model with and without winglet respectively for the maximum Reynolds number considered in this study. In this study several factors like Airstream velocity, Plan form area, Profile shape of the airfoil, Viscosity of air and Angle of attack (degrees) were considered for winglets lift and drag comparisons. The comparison was done including Coefficient of drag vs. winglet angle, lift to drag ratio Vs Reynolds number and Variation of $C_D$ with winglet angle.

Miniflaps at the trailing edges of airfoils (e.g., gurney flaps or divergent trailing edges) change the Kutta condition and thus produce higher lift. Unfortunately, however, the drag was also increased due to the flow separation downstream of this particular type of trailing edge. Therefore, the trade-off between beneficial and detrimental effects was considered by Berchart et al., (2000). Various aspects of the flow on airfoils with gurney flaps were Fluid flow, Selection of flap size and drag reduction by wake stabilization. It was possible to further reduce the drag of gurney flap by more than 48 % Berchart et al., (2000) with the wake body.

Smith et al., (2001) performed two dimensional steady state Navier-Stokes computations to determine the effect of gurney flap on NACA 4412 and NACA 0011 airfoils. There was good correlation observed between computed and experimental data. Addition of gurney flap increased the lift coefficient significantly with very little drag penalty if proper gurney flap height was selected. Nose down pitching moment also increased with gurney flap height. Flow field structure near the trailing edge shows very good resemblance with Liebeck’s hypothesis that provides the possible explanation for the increased aerodynamic performance.
Smith et al., (2001) examined the potential of multi-winglets for the reduction of induced drag without increasing the span of aircraft wings. The results show that certain multi-winglet configurations reduced the wing induced drag and improved L/D by 15-30 % compared to the baseline 0012 wing. A substantial increase in lift curve slope occurs with dihedral spread of winglets set at zero incidences relative to the wing. Dihedral spread also distributes the tip vortex. These observations in the paper supplement previous results on drag reduction due to lift reorientation with twisted winglets set at negative incidence. This study shows that negative incidence and twist of the winglets improves L/D by re-orienting the winglet lift vector forward and thus canceling part of the drag. Flat plate winglets at zero incidences improve the lift curve slope, and produce more lift than an equivalent area of the baseline wing. A combination of optimal dihedral and geometrically twisted winglets would provide enhanced L/D for subsonic wings over a range of Mach numbers.

Brown and Filippone (2003) carried out research on gurney flaps and the related high lift trailing edge devices. Investigation was done for aerofoil performances at Reynolds numbers less then or Equivalent to $10^5$ for both with the clean configuration and various gurney flap sizes. The device height is optimized, and a semi-empirical formula linking flap height to free stream speed and aerofoil chord is proposed. This analysis shows that the optimal size of the device was always below the boundary-layer thickness at the trailing edge. At angles below stall, the drag increased to the gurney flap with a height less than the trailing edge boundary-layer which was less than 20 %. For flaps of larger height, or for an aerofoil that was stalled, the drag increment was twice that of the plain aerofoil. The maximum lift to drag ratio occurs when the flap
height is about 90 % of the trailing edge boundary-layer thickness. Therefore, the flap can be applied to a number of low Reynolds number systems, including gliders, micro air vehicles, and wind turbines.

A numerical investigation was performed by Yoo (2000) to determine the effect of the gurney flap on a NACA 23012 airfoil. A Navier-Stokes code, RAMPANT, was used to calculate the flow field about the airfoil. Results were obtained using the standard k-ω two-equation turbulence model. The numerical solutions showed that the gurney flap increased both lift and drag. These suggested that the gurney flap served to increase the effective camber of the airfoil. The gurney flap provided a significant increase in the lift-to-drag ratio relatively at low angle of attack and for high lift coefficient. It turned out that 0.6 % chord size of flap was the best.

Schatz et al., (2004) described the effect of small micro-tabs (Gurney-flaps) mounted at the lower trailing edge of a HQ17 airfoil using numerical simulation. The focus of attention was mainly placed on the unsteady flow structures in the wake of the gurney flap, as these are responsible for increased induced drag. At a Reynolds number of 10^6, the flow was investigated by using steady and unsteady simulations which was based on the Reynolds-averaged Navier-Stokes equations (URANS) as well as detached eddy simulations (DES). In order to reduce the occurrence of unsteady flow structures, further simulation was performed using alternative trailing edge shapes. The results from this study show that the unsteadiness can be successfully suppressed and the drag can be reduced substantially using advanced flap concepts. In this paper the relationship between angle of attack and Transition wake was studied.
Gervois and Grenon (2009) described the design and performance analysis of a wing tip device proposed within the M-DAW project by ONERA was presented in this paper. A proto-design process was described and the device was thoroughly assessed (mainly with Reynolds-Averaged Navier-Stokes simulations). This device was a downward pointing winglet designed for a retrofit scenario (the wing could be modified only within the 96 % to 100 % bounds of the span). The downward pointing winglet reaches the M-DAW low speed target ($L/D$ increase by 2 %) when compared to the tip fence of the same span.

Chattot (2005) explained the design and analysis of winglets from an aerodynamic point of view. The effect of a small yaw angle on a wing equipped with such optimal winglets indicates that, even in the presence of viscous effects, they provide weathercock stability.

Bourdin et al., (2006) investigated a novel method of control for ‘morphing’ aircraft. They used as cant angle of $45^0$ for the winglet for maximum performances.

Myose et al., (2006) investigated the effect of a gurney flap in a compressor cascade model at low Reynolds number using tuft flow visualization in a water table facility. The results suggested that the gurney flap energizes the flow and delays the stall at large incoming flow angles. This is similar to wind turbine blades cascade with and without gurney flaps.

Watters and Masson (2007) paper presents the recent developments of a new CFD-based method aimed at predicting wind turbine aerodynamics. A comparison was done with results obtained by an actuator disk method (without
Hossain et al., (2007) describes the influences of two pair of elliptical and circular shaped winglets with the wing of the aircraft model for the reduction of induced drag without increasing the span of the aircraft. The experimental results show that lift curve slope increases by 1 – 6 % with the addition of certain winglet configurations as compared to the aircraft model with and without winglet for the maximum Reynolds number considered in the study.

Cairns et al., (2008) in their paper explored the active control surfaces on wind turbine blades for improved reliability and efficiency. Concept mechanisms were developed, demonstrated, and analyzed with regards to their deployment in current and next generation wind turbine blades.

Dam et al., (2007) describes effect of wind turbine blade tip geometry is numerically analyzed using computational fluid dynamics (CFD). An increase in loadings (particularly the normal force) towards the tip seems to be associated to a span wise flow component present for the swept- back analyzed tip.

Ferrer and Munduate (2007) analyzed the integrated loads were ranked to asses wind turbine tip overall performance. The flow physics around the airfoil was studied three rotating tip shapes and various terms like stagnation pressure, change in Re, AOA and local suction depending on the tip shape.

Dam et al., (2007) focused on the latter aerodynamic devices, their time-dependent effect on sectional lift, drag, and pitching moment, and their
effectiveness in mitigating high frequency loads on the wind turbine. The overall transient behavior of the micro flap is very similar to that of the micro tab, with a slightly faster initial response time and larger lift effectiveness due to the trailing-edge location of the former.

Gaunna & Johansen (2007) described theoretical considerations and computational results on the nature of using winglets on wind turbines. The agreement between FWLL results and CFD results in the case with winglets is not as good as in the case without winglets. Due to this, the predicted increase in $C_p$ is lower for the CFD results.

Maughmer and Bramesfeld (2008) explored the aerodynamics of a gurney-flap-equipped airfoil was explored by means of low-speed wind-tunnel experiment. As the angle of attack is decreased, the influence of a gurney flap extending from the lower surface also decreases as the flap is increasingly immersed in the thickening boundary layer. A gurney flap mounted to the upper surface behaves in the opposite way increasing the negative lift at low angles of attack and having less and less influence as the angle of attack is increased. The gurney flaps result in significantly higher drags for airfoils with extensive runs of laminar flow. This disadvantage disappears as the amount of turbulent boundary-layer flow increases, as is the case with fixed transition near the leading edge of the airfoil. Comparison was done on the aerodynamic characteristics with a 1 % gurney flap located at the trailing edge on the upper and lower surfaces and it suggests the possible location of Flaps.

Thumthae and Chitsomboom (2009) explained the numerical simulation of horizontal axis wind turbines (HAWT) with untwisted blade to determine the optimal angle of attack that produces the highest power output. The numerical
solution was carried out by solving conservation equations in a rotating reference frame wherein the blades and grids were fixed in relation to the rotating frame. Computational results of the 12° pitch angle was in agreement with the field experimental data of the national renewable laboratory (USA), for both inviscid and turbulent conditions. Numerical experiments were then conducted by varying the pitch angles and the wind speeds. The power outputs reach maximum at pitch angles: 4.12°, 5.28°, 6.66° and 8.76° for the wind speeds 7.2 m/s, 8.0 m/s, 9.0 m/s and 10.5 m/s, respectively. The optimal angles of attack were then obtained from the data.

**6.3 Methodology**

The rotor blades were modeled as briefed in Chapter 4 and their 2 % trailing edges were flapped to 35° inwards to the pressure side as shown in Figure 6.1. The rest of the procedure followed is the same as the methodology given in Chapter 4.

![Figure 6.1 Flap at the trailing edge](Image)

The blade trailing edge is flapped toward pressure side at an angle of 35° to 2 % of cord length of the airfoil as shown in Figure 6.7 Cory et al., (1998).

**6.4 Results and Discussion**

The various moments generated by the three blades with gurney flaps and the results are shown in Table 6.1
Table 6.1 Various moments generated by three blades with gurney flaps

<table>
<thead>
<tr>
<th>Zone name</th>
<th>pressure moment N-m</th>
<th>viscous moment N-m</th>
<th>total moment N-m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>Blade A</td>
<td>228578</td>
<td>51018</td>
<td>-123276</td>
</tr>
<tr>
<td>Blade B</td>
<td>3265.01</td>
<td>46279</td>
<td>184598</td>
</tr>
<tr>
<td>Blade C</td>
<td>-241204</td>
<td>64447</td>
<td>-142808</td>
</tr>
<tr>
<td>Net</td>
<td>-11361</td>
<td>16374</td>
<td>-81425</td>
</tr>
</tbody>
</table>

Power generated 443.25 kW …………………6.1

Table 6.2 Various moments generated by three blades without gurney flaps

<table>
<thead>
<tr>
<th>Zone name</th>
<th>pressure moment N-m</th>
<th>viscous moment N-m</th>
<th>total moment N-m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>Blade A</td>
<td>-324880.5</td>
<td>62489.9</td>
<td>-178690.3</td>
</tr>
<tr>
<td>Blade B</td>
<td>3625.0335</td>
<td>10285.3</td>
<td>157252.39</td>
</tr>
<tr>
<td>Blade C</td>
<td>234494.03</td>
<td>23070.5</td>
<td>-140078.8</td>
</tr>
<tr>
<td>Hub</td>
<td>10.01011</td>
<td>5.36261</td>
<td>53.04866</td>
</tr>
<tr>
<td>Net</td>
<td>-86764.25</td>
<td>95849.9</td>
<td>-161575.2</td>
</tr>
</tbody>
</table>

Power generated 265 kW ………………………6.2
Figure 6.2 shows the contours of static pressure over the entire model surfaces.

Figure 6.3 depicts the dynamic pressures over the entire model. The tip region has relatively high dynamic pressure when compared to the other regions of model.
Figure 6.4 Contours of velocity magnitude over the three blades with gurney flaps.

Figure 6.4 shows the contours of velocity magnitude wherein it is clear that the tip has maximum velocity of 45 m/s.

Figure 6.5 Velocity vectors colored by velocity magnitude (without tower)
Figure 6.5 shows the velocity vectors of the blade surfaces and it is well seen that the centre parts of all three blades have lower velocity compared to tip regions which have higher velocity.

**Figure 6.6** Contours of velocity magnitude

Figure 6.6 shows the contours of velocity magnitude over the entire model. Velocity at tip is high because of rotation of blades.

**Figure 6.7** Velocity vectors colored by dynamic pressure
Figure 6.7 shows the velocity vectors colored by dynamic pressure among the three blades.

Figure 6.8 shows the velocity vectors colored by velocity magnitude for the flapped blades.

Winglets are introduced at the top of the blade for avoiding the turbulence at the top region when it is rotation at high relative velocities. For avoiding tip region turbulence at tips when the rotating at high relative velocities the tips are introduced with winglets as shown in Figure 6.9. Further analysis is same as that followed in Chapter 4 except that the wing length is increased by one meter with S817 airfoil of same dimensions at tip and bent by 30° for a length of 0.5 m in counter clockwise direction (Gervois and Grenon, 2009).
Figure 6.10 Blades with winglet at the tips on HAWT

Figure 6.10 shows the complete assembly of HAWT with winglets at the tips of each blades. The blades are rotating anti clockwise direction. The winglets are kept at tips of the blades pointing in the clockwise direction.

Figure 6.11 Static pressure contour over entire assembly of HAWT with winglets.
Static pressure contour over entire assembly of winglet introduced HAWT is shown in Figure 6.11. The tips of the blades have maximum static pressure compared to other areas.

Figure 6.12 Velocity magnitude contour over entire assembly

The velocity magnitude contour over entire assembly of winglet introduced in HAWT is shown in Figure 6.12. As in the case of conventional HAWT the winglet introduced HAWT shows higher relative velocities at tips.

The study focused on evaluating the advantages of gurney flap geometry for the blade trailing edge and the complex mechanism of the winglet was investigated.
6.4.1 Effect of gurney flap

The introduction of gurney flap is focused to increase the aerodynamic power generation to 450 kW for 3 m/s wind speed in contrast to the existing generation of 233 kW at 3.5 m/s wind speed condition. Even though all blades are similar in size the moments generated by them differs with respect to their respective space positions. A broad description of the flow field past the rotating blade of a HAWT was given by post processing CFD data. Diagrams and plots of velocity, pressure, vortices, were presented which are suitable for understanding the physical problem. The flow field past the rotating blade of a wind turbine and the rotational effects on its boundary layer were investigated.

**Table 6.3** Moments generated by three blades without winglets on Y axis

<table>
<thead>
<tr>
<th>Zone</th>
<th>Pressure moment N-m</th>
<th>Viscous moment N-m</th>
<th>Total moment N-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade A</td>
<td>215700</td>
<td>353.745</td>
<td>216054</td>
</tr>
<tr>
<td>Blade B</td>
<td>246483</td>
<td>320.828</td>
<td>246804</td>
</tr>
<tr>
<td>Blade C</td>
<td>273427</td>
<td>322.479</td>
<td>273749</td>
</tr>
<tr>
<td>Total</td>
<td>735610.2</td>
<td>997.0519</td>
<td>736607.3</td>
</tr>
</tbody>
</table>

![Figure 6.13] Moments generated on Y axis by three blades without winglets.
The blades of the HAWT with winglets are not generating uniform moments as the case of normal HAWT. The Blade 1 which generates lower pressure moment has small amount of higher viscous moment compared to the other two blades.

6.4.2 Effect of winglets.

Table 6.4 Moments generated by three blades with winglets on Y axis

<table>
<thead>
<tr>
<th>Zone</th>
<th>Pressure moment N·m</th>
<th>Viscous moment N·m</th>
<th>Total moment N·m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade A</td>
<td>305583</td>
<td>282.609</td>
<td>305866</td>
</tr>
<tr>
<td>Blade B</td>
<td>189513</td>
<td>438.495</td>
<td>189952</td>
</tr>
<tr>
<td>Blade C</td>
<td>245269</td>
<td>345.064</td>
<td>245614</td>
</tr>
<tr>
<td>Total</td>
<td>740365.2</td>
<td>1066.168</td>
<td>741431.4</td>
</tr>
</tbody>
</table>

![Figure 6.14](image)

Figure 6.14 Moments generated on Y axis by three blades with winglet

Figure 6.14 shows the moments generated by the blades without winglets
Tables 6.3 and 6.4 show the pressure and viscous moments generated by the three blades without and with winglets respectively. There is substantial increase in the total moment generated by the HAWT with winglets.

### 6.5 Conclusions

From this Chapter 6 the following conclusions are arrived.

- A model of HAWT with flapped wings and winglets at the end of the blades can be effectively modeled for numerical simulation and analysis.
- The gurney flaps of the blades in the HAWT effectively changes the aerodynamic performances.
- At wind speeds lower than the cut in speed the gurney flapped blade of the HAWT generates excess moments.
- The introduction of gurney flaps increases the power generation from 233 kW to 450 kW for the wind speed range 3 m/s.
- The introduction of the winglets at the tip of the blades rotating at high tip speed ratio can be effectively modeled and analyzed.
- The total momentum generated by the HAWT was found to increase considerably by the introduction of winglets.