CFD Analysis of a Wind Turbine Airfoil with Flap

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WASHINGTON UNIVERSITY IN ST. LOUIS

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CFD Analysis of a Wind Turbine Airfoil with Flap

By

Heyou Tan

A thesis presented to

James McKelvey School of Engineering of Washington University in St. Louis

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for the degree of Master of Science

May 2020

St. Louis, Missouri
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Heyou Tan

Washington University in St. Louis

May 2020
Dedication

I would like to dedicate this thesis to my father (Shiming Tan) and my mother (Huijun Guo) for their unconditional support. I would never succeed without their guidance, influence and encouragement.
Abstract

CFD Analysis of a Wind Turbine Airfoil with Flap

By

Heyou Tan

Master of Science in Mechanical Engineering

Washington University in St. Louis, 2020

Research Advisor: Professor Ramesh K. Agarwal

The focus of this thesis is to evaluate the aerodynamic performance of NREL S809 airfoil (widely used airfoil for wind turbine blades) with a trailing-edge flap by numerical simulations. In the simulations, the geometry of the flap and the gap between the main element and the flap are varied. The airfoil geometry is created in Design Modeler and structured mesh around the airfoil is generated using meshing software ICEM. Simulations are performed using the Reynolds-Averaged Navier-Stokes (RANS) equations with SST k-ω, Spalart-Allmaras (SA) and Wray-Agarwal (WA) turbulence models at Reynolds number $10^6$ at angles of attack of $0^\circ$, $5^\circ$, $10^\circ$, $15^\circ$, and $20^\circ$. First, numerical solutions are validated against the experimental data for S809 airfoil without flap. Then the numerical simulations are conducted with a triangular Gurney flap at various angles of attack. The lift coefficient and the drag coefficient are calculated and are compared with S809 airfoil without flap to evaluate the effect of flap on the airfoil performance. The pressure contours, turbulent kinetic energy contours, and streamlines are plotted and compared for airfoil without and with flap to analyze the details of the flow field. Computed results show that the presence of trailing-edge flap provides higher lift and lift-to-drag ratio compared to original airfoil demonstrating its promise for larger wind energy extraction.
Chapter 1: Introduction

This chapter provides the motivation behind this research and scope of this thesis. The focus of the thesis is on research in the area of wind energy, in particular on evaluating the aerodynamic performance of NREL S809 airfoil (widely used airfoil for wind turbine blades) with a trailing-edge flap by numerical simulations.

1.1 Motivation

As the energy demand has been increasing because of increase in world population and rising standards of living, there has been large increase in consumption of fossil fuels and associated Greenhouse Gas (GHG) emissions impacting the climate and global warming. To address this problem, there has been increased emphasis on replacing the fossil fuels with renewable energy sources such as wind, solar and biomass. Among renewable energy sources, wind energy has seen exponential increase worldwide in past decade. The wind turbines have been installed on land as well as off-shore all over the world; majority of them being the Horizontal-Axis-Wind Turbines (HAWT). According to Wind Technologies Market Report [1] by the U.S. Department of Energy (DOE), wind power reached a peak of 7,017MW in the United States in 2017 with $11 billion investment.

It is therefore of great interest to improve the aerodynamic performance of wind turbines. There have been many efforts to improve the power coefficient of the turbine by blade optimization, by adding flaps and active flow control devices. In this thesis, we consider the addition of a simple flap and a Gurney flap to a well-known wind turbine airfoil, NREL S809 and evaluate its aerodynamic performance by numerical simulation.
1.2 Scope of the Thesis

One of the key goals of this thesis is to evaluate the aerodynamic performance of NREL S809 by deploying two types of flaps (a plain flap and a Gurney flap) at the trailing-edge of the airfoil. Numerical simulations are performed to determine the lift coefficient and lift-to-drag-ratio [2] at various Reynolds numbers and free-stream angles of attack for various flap angles.

The NREL S809 is a laminar-flow airfoil with 21% thickness and is widely used in HAWTs [3, 4]. Numerical simulations are performed by solving the Reynold-Averaged Navier-Stokes (RANS) equations in conjunction with Spalart-Allmaras (SA), SST k-ω and Wray-Agarwal (WA) turbulence models. The commercial CFD software ANSYS Fluent is used in the simulations. Wind velocity is obtained from IEC Wind Class 1 datasheet. The flow is at a very low Mach number and is considered as incompressible and the Reynolds number is one million at which the experimental data is available for validation of CFD results and evaluation of the accuracy of various turbulence models. The numerical solutions are obtained at angles of attack varying from 0 to 20 degrees and flap deflection angles varying from -5 to 10 degrees. Geometry modeling and mesh generation is accomplished by using the ICEM software. CFD Post is used to calculate the lift coefficient, the drag coefficient and to plot the contours of flow variables.
Chapter 2: CFD Simulation and Validation of Flow past S809 Airfoil

2.1 Physical Model

In a paper by Douvi and Margaris [5], a comparison between the aerodynamic performance of NACA 0012 and NREL S809 wind turbine airfoil was conducted, and it was concluded that S809 airfoil has better performance. In this chapter, we consider S809 airfoil and perform numerical simulations at various angles of attack at Re = 1x10^6 using three turbulence models, namely the Spalart-Allmaras (SA), SST k-ω and Wray–Agarwal (WA) model and compare the results with the experimental data. Figure 2.1 shows the geometry of the S809 airfoil.

Figure 2.1: Geometry of S809 Airfoil

It is a 21% thick airfoil with large camber; as a result it experience lift even at zero degree angle of attack. Experimental data shows that there is laminar flow over the forward half of the airfoil when angle of attack is < 5° and backward half of the airfoil has separation bubble with turbulent reattachment [6]. As angle of attack increases beyond 5°, separation region moves towards the
leading-edge, and finally stall occurs at approximately 20° angle of attack. In the simulation, the length of airfoil chord is set at 1m and angle of attack is varied from 0° to 20°.

2.2 CFD Simulation

2.2.1 Simulation Method

The commercial CFD software ANSYS FLUENT 19.2 is employed in the simulations. The steady incompressible Reynolds-Averaged Navier-Stokes (RANS) equations are solved using the finite volume method with SST k-ω, Spalart-Allmaras and Wray-Agarwal turbulence models. The SST k-ω turbulence model [7] is a two-equation eddy viscosity model which combines the best characteristics of the k-ω and k-ε turbulence models in the near wall and free-stream regions respectively. The Spalart-Allmaras turbulence model [8] is the most widely used one-equation linear eddy-viscosity turbulence model for aerodynamic flows. The Wray-Agarwal [9] is a most recently developed one-equation model which also combines the best features of the k-ω and k-ε turbulence models in the near wall and free-stream regions respectively. It has been applied to several canonical benchmark flow cases [9] and has shown improved accuracy over the SA model and competitiveness with the SST k-ω model; in this thesis “Wray-Agarwal 2017m” version of the model is used by creating a UDF file for Fluent. All computations are performed in double precision. A second order upwind scheme is utilized for the convection terms and a second order central difference scheme is used for the diffusion terms. The SIMPLE algorithm is employed for the pressure-velocity coupling.
2.2.2 Boundary Conditions

For S809 airfoil in the unbounded flow, the inlet and outlet boundaries of the computational domain are located at a distance 40c away from the airfoil. Standard air parameters include the environmental temperature = 298K, air density $\rho = 1.225 \text{ kg/m}^3$ and the viscosity $\mu = 1.7894 \times 10^{-5}$ kg. m/s. The inlet free stream velocity is set at 15m/s with Reynolds number = $10^6$, outlet gauge pressure is 0 Pascal. The airfoil is set as a no-slip stationary wall.

2.3 Governing Equations

The incompressible Reynolds-Averaged Navier–Stokes (RANS) equations are used for simulation of turbulent flow; they can be written as

\[
\frac{\partial U_i}{\partial x_i} = 0
\]

and

\[
\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j^2}
\]

where $U_i$ is the time-averaged velocity, $P$ is time-averaged pressure, $\rho$ is the time-averaged density, $\nu$ the total viscosity as a sum of the laminar kinetic viscosity and the turbulent eddy viscosity which is obtained from a turbulence model.

2.4 Mesh Generation

In the meshing process using ICEM, a C-H computational domain is selected with 20 times the chord length the inlet C-boundary from the airfoil and 20 times the chord length the outlet H-boundary from the airfoil. After conducting the mesh independent study on a sequence of three meshes, a structured mesh of 150,000 quadrilateral cells is selected to achieve the mesh independent solution. The first grid point from the boundary is at a distance of $2.3 \times 10^{-5}$m from
the wall with and \( y+ < 1 \) as shown in Fig 2.2. ICEM is used to check the mesh quality. Figure 2.3 (a) shows the indicator of orthogonal quality of the mesh, which is 0.96. Figure 2.3(b) shows another mesh quality method namely the aspect ratio of the cells in the domain which is 1.26. These two criteria attest to the high quality of the mesh which assure the higher accuracy of the numerical solution.

![Fig 2.2: Zoomed-in View of Structured Grid around the Airfoil](image1.png)

![Fig 2.3: (a) Orthogonal quality of the mesh and (b) Aspect ratio quality of mesh](image2.png)

**2.5 Validation of the Solution Methodology**

Experimental data of Xu et al. [10] is used to validate the numerical solution methodology.
Figures 2.4 and 2.5 show the comparison between computations and experimental data for S809 airfoil for lift and drag coefficient respectively for a range of angles of attack -5 degree to 25 degree. The computations are performed at Reynolds number of one million using the RANS equations with SA model. It can be seen from these figures that there is close agreement between the experimental data and computations when angle of attack < 17.5 degree; however, when angle of attack becomes > 17.5 degree, there is disagreement between computations and experimental data since the airfoil experiences stall which is very difficult to compute. These results validate the CFD methodology employed.
Chapter 3: S809 Airfoil with Plain Flap

3.1 Geometry and Flow Field Conditions

Barlas and Lackner [11] showed that a trailing-edge flap with 10% chord length of the main airfoil chord improves the aerodynamic performance of S809 airfoil; they considered flap deflection angles ranging from -5 to 10°. Unsteady fluctuations on blades considerably affect the lifetime and reliability of wind turbines [10], therefore, flap deflection angle and flap gap should be taken into account when designing a multi-element wind turbine airfoil. In our simulation, flap gap distance is set 1mm, since greater flap gap can result in poor aerodynamics performance. Figure 3.1 shows the geometry of S809 airfoil with flap and Table 3.1 gives the various parameters of the airfoil.

<table>
<thead>
<tr>
<th>S809 airfoil</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length</td>
<td>1000 mm</td>
<td>Maximum thickness</td>
<td>210 mm</td>
<td>Length of flap</td>
<td>100 mm</td>
<td>Angel of attack of main airfoil</td>
</tr>
<tr>
<td>Length of flap</td>
<td>100 mm</td>
<td>Flap deflection</td>
<td>-5 to 10 deg.</td>
<td></td>
<td></td>
<td>Flap gap</td>
</tr>
</tbody>
</table>

Figure 3.1: Geometry of S809 airfoil with trailing-edge flap
3.1.1 Flow Field Conditions

Flow field conditions are the same as those for the S809 airfoil given in Chapter 2. The only difference is the presence of the flap. The flap angle of 2.5 degree is used in the simulations reported in this chapter. The computations are performed for angles of attack of 0, 5, 10, 15 and 20 degree using the SA, SST k-ω and WA models. All the models give results very close to each other. In the following sections, the velocity and pressure contours are plotted at various angle of attack to show the separation region on the airfoil and its effect on the flap.

3.2 Computational Results

3.2.1 Computations with Spalart-Allmaras (SA) Turbulence Model

Figure 3.2 shows the velocity contours at five different angles of attack. It can be seen that as the angle of attack increases above 5°, separation occurs on the upper surface of the airfoil behind the mid-way point and moves forward towards the leading edge as the angle of attack continues to increase and finally covers the entire upper surface originating from the leading edge. At angles of attacks > 5°, the upper surface of the flap is always in the separated flow region from the main element of airfoil reducing the effectiveness of the flap. Figure 3.3 shows the pressure coefficient contours. From the pressure contours, it can be seen that pressure on the lower surface of the airfoil is highest at 15° angle of attacks resulting in largest lift. At angles of attack > 15°, the lift decreases and drag increases because of massive flow separation on the upper surface of the airfoil.
Angle of attack = 0 degree

Angle of attack = 5 degrees

Angle of attack = 10 degrees

Angle of attack = 15 degrees

Angle of attack = 20 degrees

Figure 3.2 Velocity Contours on S809 Airfoil with Plain Flap using SA model
Angle of attack = 0 degree

Figure 3.3 Pressure Contours on S809 Airfoil with Plain Flap using SA model
3.2.2 Computations with SST k-ω Turbulence Model

Figure 3.4 and 3.5 show the velocity and pressure contours around the S809 airfoil with plain flap at various angles of attack. These are very similar to those obtained with SA model in section 3.1.1 with some minor differences especially in pressure contours at high angles of attack. But overall, the results are the same for both lift and drag coefficient at all angles of attack as shown in Figures 3.8 and 3.9 respectively.
Angle of attack = 20 degree

Figure 3.4: Velocity Contours around S809 Airfoil with Plain Flap using the SST k-ω model

Angle of attack = 0 degree

Angle of attack = 5 degree

Angle of attack = 10 degree

Angle of attack = 15 degree
Angle of attack = 20 degree
Figure 3.5 Pressure Contours around S809 Airfoil with Plain flap using SST k-ω model

3.2.3 Computations with Wray-Agarwal (WA) Turbulence Model

Figure 3.6 and 3.7 show the velocity and pressure contours around the S809 airfoil with plain flap at various angles of attack. These are very similar to those obtained with SA and SST k-ω models in section 3.1.1 and 3.1.2 respectively with some minor differences especially in pressure contours at all angles of attack. It can be seen from Figure 3.8 and 3.9 respectively that the lift coefficient computed by the WA model is slightly higher than that computed by the SA and SST k-ω models while the lift coefficient computed by the WA model is slightly lower than that computed by the SA and SST k-ω models. But overall the results are the same for both lift and drag coefficient at all angles of attack for all three models as shown in Figures 3.8 and 3.9 respectively.
Angle of attack = 0 degree

Angle of attack = 5 degree

Angle of attack = 10 degree

Angle of attack = 15 degree

Angle of attack = 20 degree

Figure 3.6: Velocity Contours around S809 airfoil with Plain Flap Using WA Model
Angle of attack = 0 degrees

Angle of attack = 5 degree

Angle of attack = 10 degree

Angle of attack = 15 degree

Angle of attack = 20 degree

Figure 3.7: Pressure Contours around S809 Airfoil with Plain Flap using WA model
3.2.4 Lift and Drag Coefficients

The lift and drag coefficient curves for S809 airfoil with plain flap at various angles of attack with flap angle of 2.5° are shown in Figures 3.8 and 3.9 respectively. The flow at angle of attack of 20° was found to be unsteady; therefore, the mean values are used in the lift and drag coefficient curves in Figures 3.8 and 3.9.

In Figure 3.8, the lift coefficient increases almost linearly with angle of attack until $\alpha = 15^\circ$ when it decreases due to massive separation and the airfoil experiences stall. It can be noted that WA model gives slightly higher value of lift coefficient compared to those predicted by SA and SST k-\omega model for the entire angle of attack range. From Figure 3.9, it can be seen that the drag coefficient increases very slowly for $\alpha < 10^\circ$ but sharply increases when $\alpha > 10^\circ$ due to large separation on the upper surface of the airfoil. The drag coefficient predictions from WA model are slightly lower but the predictions from all three models are very close.

![Variation of lift coefficient with angle of attack of S809 airfoil with plain flap](image)

Figure 3.8: Variation of lift coefficient with angle of attack of S809 airfoil with plain flap
3.2.5 Pressure Coefficient

Fig 3.10 shows the computed pressure coefficient distributions on the airfoil with plain flap for three flap deflection angles of different flap deflection angles of 0°, 2.5° and 5° for Re = 1 million and free stream angle of attack $\alpha = 5$ degree. This figure shows that as the flap deflection angle increases, there is change in the pressure distribution signifying the increase in lift.

Fig. 3.10 Pressure coefficient distributions on S809 airfoil with plain flap at Re $= 10^6$, $\alpha = 5$ deg. with different flap deflection angles
Chapter 4: S809 Airfoil with Gurney Flap

4.1 Geometry and Flow Conditions

In this chapter, a triangle-shaped Gurney Flap (GF) is selected to combine with S809 airfoil as shown in Figure 4.1; GF increases the maximum lift by altering the Kutta condition at the trailing-edge of the airfoil. The wake behind the flap is a pair of counter-rotating vortices which benefit the overall lift-to-drag ratio if the flap is tailored appropriately.

![Fig 4.1 Geometry of S809 Airfoil with Triangle-Shaped Gurney Flap](image)

4.1.1 Flow Field Information

Flow field conditions are the same as those for the S809 airfoil given in Chapter 2. The only difference is the presence of the Gurney flap. The computations are performed for angles of attack of 0, 5, 10, 15 and 20 degree using the SA, SST k-ω and WA models. All the models give results very close to each other. In the following sections, the velocity and pressure contours are
plotted at various angles of attack to show the separation region on the airfoil and its effect on the flap.

4.2 Computational Results

4.2.1 Computations with Spalart-Allmaras (SA) Turbulence Model

Figure 4.2 shows the velocity contours around the airfoil with Gurney flap at various angles of attack. It can be seen that as the angle of attack increases above 5°, separation begins to occur on the upper surface of the airfoil upstream of the trailing edge and the separation point is just behind the mid-way point on the surface of the airfoil at α =10°. The separation point moves forward towards the leading edge as the angle of attack continues to increase and finally covers the entire upper surface originating from the leading edge. At angles of attacks > 5°, the upper surface of the flap is always in the separated flow region from the main element of airfoil reducing the effectiveness of the flap.

![Angle of attack = 0 degree](image1)

![Angle of attack = 5 degree](image2)

20
Figure 4.2 Velocity contours around S809 Airfoil with Gurney Using the SA model

Figure 4.3 shows the pressure coefficient contours around the airfoil with Gurney flap at different angles of attack. When angle of attack is $>10^\circ$, there is high pressure region on the lower surface of the airfoil near the leading edge as well as at the trailing edge due to the presence of Gurney flap. The suction on the upper surface also increases. When angle of attack is $<10^\circ$, the high-pressure region on the lower surface near both the leading and trailing edge decreases, and the high-pressure region near the trailing edge almost disappears. When the angle
of attack is 15°, there is large pressure generated at lower surface of the airfoil, which gives the highest lift coefficient at this angle of attack. At angles of attack > 15°, the lift decreases and drag increases because of massive flow separation on the upper surface of the airfoil.

Figure 4.3 Pressure Contours around S809 Airfoil with Gurney Flap using the SA model
4.2.2 Computations with SST k-ω Turbulence Model

Figure 4.4 and 4.5 show the velocity and pressure contours around the S809 airfoil with Gurney flap at various angles of attack. These contours are very similar to those obtained with SA model in section 4.1.1 with some minor differences especially in pressure contours at high angles of attack. But overall, the results are the same for both lift and drag coefficient at all angles of attack as shown in Figures 4.8 and 4.9 respectively.
Angle of attack = 20 degree

Figure 4.4 Velocity Contours around S809 Airfoil with Gurney flap using the SST model

Angle of attack = 0 degree

Angle of attack = 5 degree

Angle of attack = 10 degree

Angle of attack = 15 degree
Angle of attack = 20 degree
Figure 4.5 Pressure Contours around S809 Airfoil with Gurney Flap using SST model

4.2.3 Computations with Wray-Agarwal (WA) Turbulence Model

Figure 4.6 and 4.7 show the velocity and pressure contours around the S809 airfoil with Gurney flap at various angles of attack. These are very similar to those obtained with SA and SST k-ω models in section 4.1.1 and 4.1.2 respectively with some minor differences especially in pressure contours at all angles of attack. It can be seen from Figure 4.8 and 4.9 respectively that the lift coefficient computed by the WA model is slightly higher than that computed by the SA and SST k-ω models while the drag coefficient computed by the WA model is slightly lower than that computed by the SA and SST k-ω models. But overall the results are the same for both lift and drag coefficient at all angles of attack for all three models as shown in Figures 4.8 and 4.9 respectively.
Angle of attack = 0 degree

Angle of attack = 5 degree

Angle of attack = 10 degree

Angle of attack = 15 degree

Angle of attack = 20 degree

Figure 4.6 Velocity Contours around S809 Airfoil with Gurney Flap using the WA model
Figure 4.7 Pressure Contours around S809 Airfoil with Gurney Flap Using the WA model
4.3 Lift and Drag Coefficients

4.3.1 Lift and Drag Coefficients of S809 Airfoil with Gurney Flap

Figures 4.8 and 4.9 show the variation in lift and drag coefficient with angle of attack for S809 airfoil with triangle-shaped obtained with SA, SST k-ω and WA models. In Figure 4.8, the lift coefficient increases almost linearly with angle of attack until $\alpha = 15^\circ$ when it decreases substantially at $\alpha = 20^\circ$ (this is much lower than that for the airfoil with plain flap as shown in Figure 3.8) due to massive separation and the airfoil experiences stall. It can be noted that WA model gives slightly higher value of lift coefficient compared to those predicted by SA and SST k-ω model for the entire angle of attack range. From Figure 4.9, it can be seen that the drag coefficient increases very slowly for $\alpha < 10^\circ$ but sharply increases when $\alpha > 10^\circ$ due to large separation on the upper surface of the airfoil. The drag coefficient predictions from WA model are slightly higher but the predictions from all three models are very close.

![Lift Coefficient vs Angle of Attack](image)

Fig 4.8 Variation in lift coefficient with Angle of Attack of S809 airfoil with Triangle Gurney Flap
4.3.2 Lift and Drag Coefficients of S809 Airfoil with Plain Flap and Gurney Flap for Various Flap Deflection Angles

Figure 4.10 shows the variation in lift coefficient of S809 airfoil with plain and Gurney flap for flap deflection angle varying from -5° to +10° for free stream angles of attacks of 0°, 2.5° and 5°. It can be seen that the lift coefficient increases as the flap deflection angle increases and also it increases as the free stream angle of attack increases. Furthermore the lift coefficient curves for airfoil with Gurney flap are consistently higher than the lift coefficient curves for airfoil with plain flap. These results demonstrate that Gurney flap is more effective in improving the aerodynamic performance of S809 compared to plain flap.

Figure 4.11 shows the variation in lift to drag ratio of S809 airfoil with plain and Gurney flap for flap deflection angle varying from -5° to +10° for free stream angles of attacks of 0°, 2.5° and 5°. It can be seen that the lift to drag ratio also increases as the flap deflection angle increases and...
also it increases as the free stream angle of attack increases. Furthermore the lift coefficient and lift to drag ratio curves for airfoil with Gurney flap are consistently higher than the lift coefficient and lift to drag ratio curves for airfoil with plain flap. These results demonstrate that Gurney flap is more effective in improving the aerodynamic performance compared to plain flap.

![Graph](image)

**Fig 4.10 Variation in Lift Coefficient with Flap Deflection Angle of Plain and Gurney Flap**

![Graph](image)

**Fig 4.11 Variation in Lift to Drag Ratio with Flap Deflection Angle for S809 Airfoil with Plain Flap and Gurney Flap**
Chapter 5: Conclusions and Future Work

In this thesis computations have performed by solving the Reynolds-Averaged Navier-Stokes equations in conjunction with Spalart-Allmaras (SA), SST k-ω and Wray-Agarwal (WA) turbulence model for flow past an S809 airfoil with plain flap and a triangular Gurney flap at various free stream angles of attack varying from 0 to 20 degrees at Re = 1 million. The results for lift and drag coefficient show that there is very small variation due to the turbulence model used and also due to the type of flap, plain vs. Gurney. The results from SA and SST k-ω model almost overlap each other while the results from WA model predict slightly higher lift coefficient and slightly lower drag coefficient at all angles of attack for moderate flap deflection angle of 2.5°. However, flap deflection angle has significant effect on both lift and drag coefficient. As the flap deflection angle increases from -5° to 10°, both the lift and drag coefficients increase with Gurney flap showing larger increase compared to plain flap. Effect of various parameters such as flap gap, geometry of the flaps, Reynolds numbers, roughness of the surface etc. should be investigated in the future work. In addition, S809 with both plain and Gurney flap should be shape optimized to improve its aerodynamic performance.
References


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Degrees

M.S. Mechanical Engineering, April 2020

B.S., Marine Engineering, July 2017