Dept. of Mech. Eng.
CUET

Published Online March 2019 (http://www.cuet.ac.bd/merj/index.html)

Mechanical Engineering Research Journal

Vol. 11, pp. 7–12, 2018

ISSN: 1990-5491

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF SERRATED GURNEY FLAP OVER A NACA 2412 AIRFOIL

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Abstract: Gurney flap, a small flat plate generally installed at the suction side of a wing. This device stabilizes the wake which ensures laminar flow over the wing with minimum aerodynamic disturbances and shifts the shock in case of high speed flows. The airfoil shapes developed by the National Advisory Committee for Aeronautics (NACA) are known as NACA airfoils. This study investigated the aerodynamic effect of serrated Gurney flap on a NACA 2412 airfoil. This involves a three-dimensional numerical and a wind tunnel investigation of the effectiveness of Gurney flap. Flap height ranges from 2% to 5% C and the serration depth and width were 0.01C which came into two shapes; triangular and square. The numerical analysis was performed using CFD software and the experimental validation was conducted in low speed wind tunnel under subsonic Mach number. The serrations tend to increase lift to drag ratio significantly and square serration provides the best performance rather than triangular serrated flap. The investigation concludes with a suggestion that serrated Gurney flap with a height of 2% chord with square serrations can be installed perpendicular to chord and as close to the trailing edge as possible to obtain maximum lift with minimum drag penalty.

Key words: *Computational Fluid Dynamics, Serrated Gurney flap, Flow control,* *Aerodynamic characteristics, Lift enhancement.*

NOMENCLATURE

Symbol	Meaning	Unit
C	Chord length	m
V	Velocity of air	m/s
L	Lift force	N
D	Drag force	N
C_D	Drag coefficient	Dimensionless

C_L	Lift coefficient	Degree
AOA	Angle of attack	J
K	Turbulent kinetic energy	m^2/S^3
ϵ	Turbulent dissipation	

1. INTRODUCTION

High-lift aerodynamics continues playing an important role in the design of new aircrafts with maximum utilization of fuel and technology available. An effective high-lift system is necessary in order to climb to the cruise altitude at take-off and to be able to fly at the necessary low maneuver speeds in case of landing. Aerodynamic stability and flight behavior of the modern aircrafts is manipulated using aileron, elevators or flap by controlling the airflow toward the wing. The trailing edge geometry exerts a great influence on the performance of the aircraft. The integration of the gurney flap at the trailing edge has been proved to be aerodynamically beneficial. It works by separating the air flow turning over the backside of the flap near the trailing edge. So, the pressure is decreased on the suction side and increased on the pressure side. This results in an increase in lift of the airfoil and a shift in the zero lift angle of attack [2] and pressure on airfoil surface. This reversed flow region is consists of two contra-rotating vortices which altered the Kutta condition and circulation in the region as shown in Fig. 1. This ensures an increment in lift force, slight reduction in drag, laminar flow on the suction side of the wing and thereby stabilizes wake. An increase in the lift to drag ratio makes it possible to attain cruise altitude faster and stepper take off as well as reduces the noises being imparted. The effectiveness of Gurney flap is dependent on the size of the flap and the location and on the ratio of the velocity of the flow on the upper surface to the mean velocity of the lower surface. [3].

The forerunner of investigations on gurney flap was Liebeck, conducted first wind tunnel experiments on gurney flap

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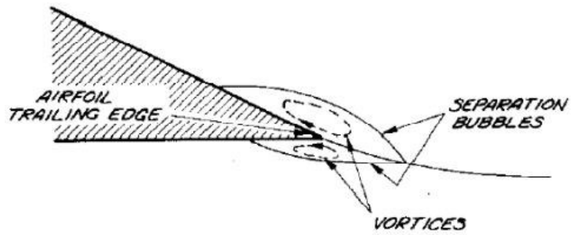
aiming to determine the lift and drag characteristics. He found that there is a lift increment at every angle of attack and existence of a separation bubble on the upper surface of the airfoil along with two counter rotating vortices at the trailing edge [4]. Reynolds-averaged Navier-Stokes (RANS) computations made by Jang *et al.* [5], Yoo [6], and Li *et al.* [7] have verified the lift enhancement of gurney flap in their experiments. Their findings coincides with Liebeck and suggested that a small recirculation zone would be formed upstream of the flap that matches well with the experimental data. They also found that drag in somehow decreased near the maximum lift and spectra from the LDA measurements and smoke visualizations ensured the presence of a Karman vortex street.

(a) Conventional airfoil



(b) Airfoil with a Gurney flap

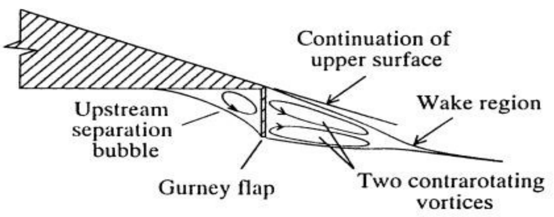


Fig. 1 Hypothesized trailing edge flow structure for a (a) Conventional airfoil (b) airfoil with a Gurney flap [1].

The earlier numerical investigations along with experimental evaluations by Fripp and Hopkins [8], Myose *et al.* [9], and Jeffrey [10], used panel methods to model sections fitted with gurney flap. Their results showed that gurney flap provided increased lift and nose-down pitching moment associated with decreased drag and the flap delayed the stall at large incoming flow angles. The current research is going on for their use in turbomachines [11].

This study is undertaken with the aim of determining the influence of the serrations on the airfoil performance for low Reynolds number in a systematic manner. The main objective of this investigation stems from the previous studies made on gurney flap and selecting the best height of the flap with serration for subsonic flow condition through validation. Gurney flap was analyzed for four different heights ranging from 2% to 5% at the trailing edge perpendicular to the chord for angle of attack ranging from 0° to 24° with triangular and square serration.

2. INVESTIGATION APPROACH

2.1 Governing Equations

Computational Fluid Dynamics (CFD) refers to the solving a set of equations to predict the flow field of any investigation. Now-a-days CFD software is very widely used and a number of flexible commercial software is developed to study the fluid flow problems. For this investigation, two equation turbulence model namely the k- ε model is used. This model is based on the fundamental concepts in physics of conservation of mass, momentum and energy along with two extra transport equations to represent the turbulent properties of the flow [12].

The continuity equation is imprinted as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j) = 0 \quad (1)$$

The momentum equation is imprinted as:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + S_M \quad (2)$$

Transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k U_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon U_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\vartheta \epsilon}} + C_{1\epsilon}\frac{\epsilon}{k}C_{3\epsilon}p_b + S_\epsilon \quad (4)$$

Where,

$$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right], \eta = S\frac{k}{\epsilon}, S = \sqrt{2S_{ij}S_{ij}}$$

Model constants are:

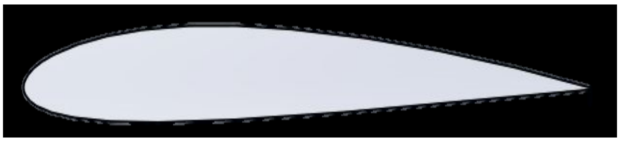
$$C_{1\epsilon} = 1.44,\ C_2 = 1.9,\ \ \sigma_k = 1.0, \sigma_\epsilon = 1.2$$

In the above equations, P_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, calculated in same manner as standard k- ε model. Here, P_b is the generation of turbulence kinetic energy due to buoyancy, calculated in same way as standard k-ε model.

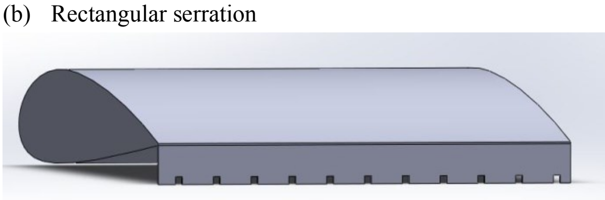
2.2 CAD Model and Mesh Generation

The three dimensional CAD model was built with SolidWorks using the 'Curves using XYZ point' function as shown in Fig. 2. Chord length was taken 200 mm and span was taken 120 mm for the convenience of using the airfoil in wind tunnel.

(a) NACA 2412 with plain flap



(b) Rectangular serration



(c) Triangular serration

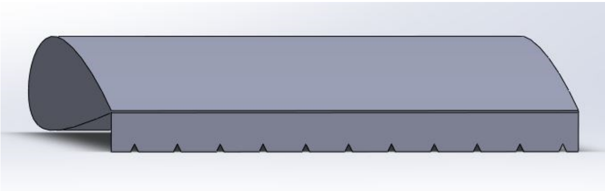


Fig. 2 CAD model of NACA 2412 with Gurney flap and serrations.

The computational fluid domain is assumed to be made of solid air interface. The domain consists of a semicircle and a rectangular shaped contour around the airfoil. A fine mesh results in higher number of calculations and thereby makes the simulation time longer. For this investigation, a structured triangular mesh was used as shown in Fig. 3.

In this investigation, the software was run in an implicit pressure base, the simple pressure-velocity coupling for both the first and second order. The second order upwind scheme was used for higher accuracy. Wall boundary conditions were applied to the wind tunnel walls and the airfoil surface. A “velocity-inlet” condition was imposed for the inlet with a speed of 5m/s. The outlet was set to “pressure-outlet”. For inflow turbulence, the intensity and viscosity ratio specification method was specified with a turbulence intensity of 1%. The convergence criterion was prescribed as the solution reached a steady state condition where all the residuals are set to any constant values. The double precision parameter was set for precise results.

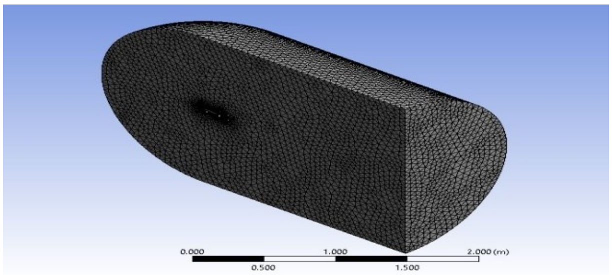


Fig. 3 Mesh generation along airfoil.

2.3 Experimental Setup

Prototyping of an airfoil body is designed to explore the variation of results by comparing the simulated and experimented outcome. A prototype of NACA 2412 with gurney flap for different height and serrations was built for wind tunnel experiment with the predefined chord length of 200mm and span of 120mm. The flaps were made of mild steel and heights were 2% chord (4mm), 3% chord (6mm), 4% chord (8mm) and 5% chord (10mm). The serrations were made with depth and width of 0.01C (2mm). The prototype fabricated in workshop was not as precise as wished for as shown in Fig. 4.

Wind tunnel testing is an effective approach to visualizing what is happening to the flow and surrounding conditions. The experimental investigation was conducted in the wind tunnel of Chittagong University of Engineering & Technology. The wind tunnel is made in the shape of a converging-diverging nozzle to obtain the required flow manipulation and a working section where the model was mounted for the test. In this study, the free stream velocity was 5 m/s which yield the Reynolds number of 68,474 based on the centerline chord of the airfoil.

Lift and drag forces were calculated using force balance setup which had two degrees of freedom. Rotation sting was used to rotate the airfoil for setting up the different angle of attack and airspeed was measured by an anemometer. A honeycomb was implemented in front of the test section in the wind tunnel to reduce flow turbulence and maintaining a steady laminar flow during the study as shown in Fig. 5.

Fig. 4 Fabricated prototype of NACA 2412 without and with 3% clean flap.

Fig. 5 Wind tunnel setup.

3. RESULTS AND DISCUSSION

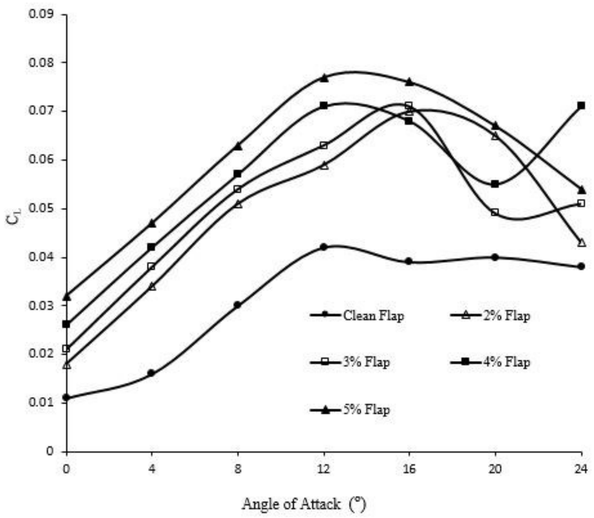
For the purpose of CFD validation, the values obtained from CFD analysis of NACA 2412 with square and triangular serration at an angle of attack ranging from 0º to 24º were compared with the experimental results from the wind tunnel data on the airfoil of similar dimensions and profile at the same Reynolds Number.

After completing the CFD analysis of 3D wing with different flap height with serrations for the different angle of attack, a comparison was made with results obtained from wind tunnel experiment on the basis of the values of C_L, C_D and coefficient of lift to drag ratio (C_L/C_D).

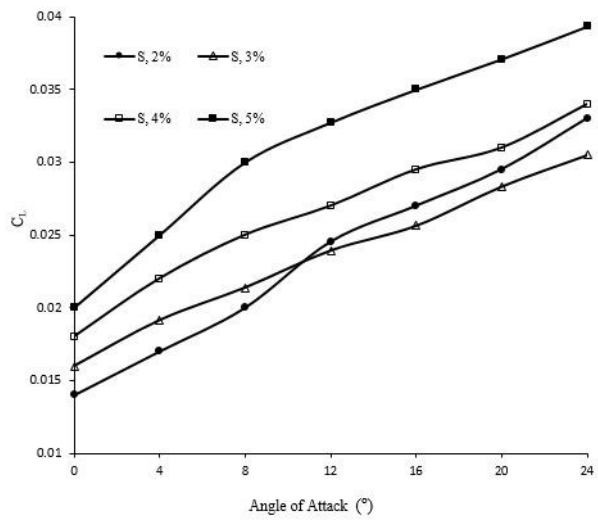
Figure 6 shows the variations of C_L for plain flaps and flaps with square and triangular serration for the different angle of attack. Obviously, an airfoil with plain gurney flap will increase the lift than without gurney flap. This increment in the lift is accompanied by an increase in skin friction drag as shown in Fig. 7. That means drag is more than a clean wing in wing with gurney flap. The lift increment is higher with the increment of flap height as well as drag force. The 2% gurney flap proved to be better among others as it has the maximum lift coefficient and minimum drag for this study.

Table 1 shows the percent increase in the maximum lift coefficient and ratio of coefficient of lift to coefficient of drag as a function of the angle of attack. The increase of maximum C_L/C_D is 21.36%, 11.63%, 9.57% and 5.06% for 2, 3, 4, 5% gurney flap without serration. The increment in the lift to drag ratio was gradually reduced with increment in lift coefficient which means serrated flap is much more effective than clean flap. The square serration increased the lift to drag ratio by 22.39% and the triangular serration increased 14.73%.

(a) Clean flap



(b) Square serrated flap



(c) Triangular serrated flap

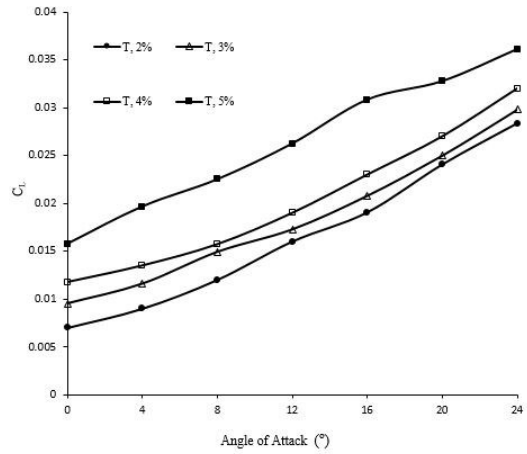
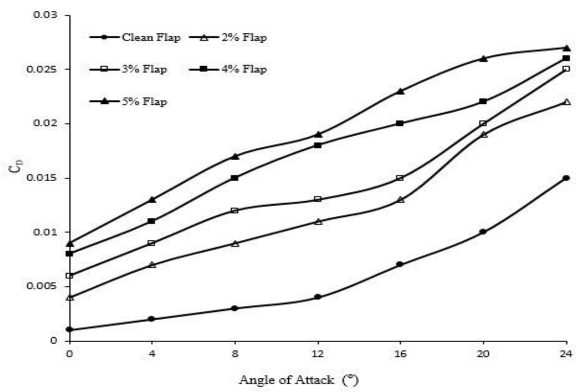


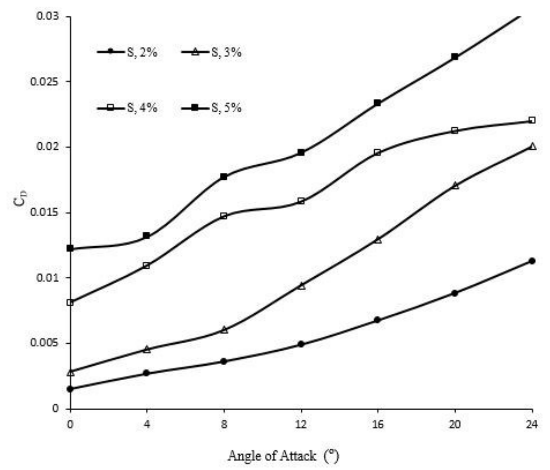
Fig. 6 Comparison of drag and lift coefficient for (a) clean flap (b) Square serrated flap and (c) Triangular Square.

Comparison of drag coefficient produced by adding gurney flap was represented by Fig 6. The gurney flap increases drag force wherever it is mounted for both serrations. The drag increments are drastic in case of 3, 4 and 5% flap and thereby lift to drag ratio decreases. The drag force sharply increases in case of a small angle of attack and significantly changes before the stall.

(a) Clean flap



(b) Square serrated flap



(c) Triangular serrated flap

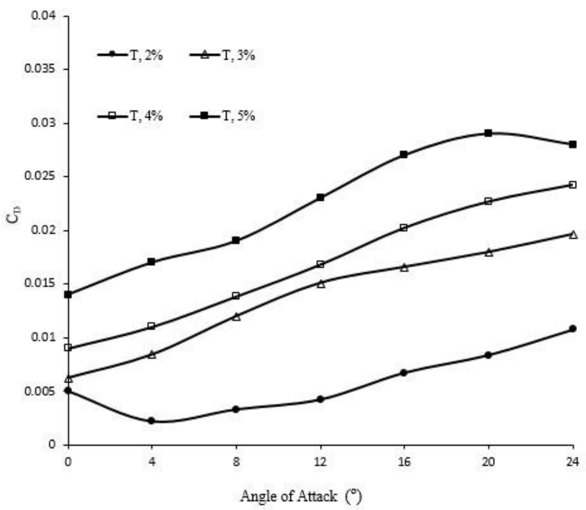


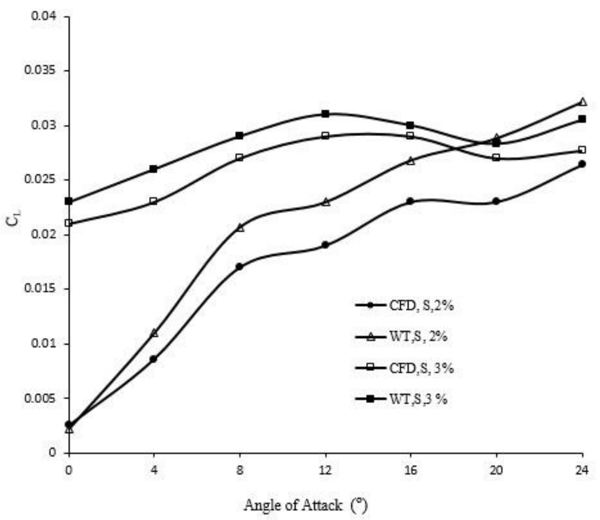
Fig. 7 Comparison of drag coefficient for (a) clean flap (b) Square serrated flap and (c) Triangular Square serrated flap.

Table 1 Percent increase in the maximum lift coefficient and ratio of coefficient of lift to coefficient of drag

Gurney flap heights	2% C	3% C	4% C	5% C
% Increase of maximum lift coefficient	6.54%	14.42%	17.32%	18.16%
% Increase of maximum C_L/C_D	21.36%	11.63%	9.57%	5.06%

After reviewing all the results from the investigation, it can be clearly said that the gurney flap with 5% C height produces maximum lift but increased drag made that inefficient. Flap with 2% C height provided the best performance in these conditions. Serrations were made to increase the effectiveness of the flap.

(a) Airfoil with 2 and 3 % Gurney flap



(b) Airfoil with 4 and 5 % Gurney flap

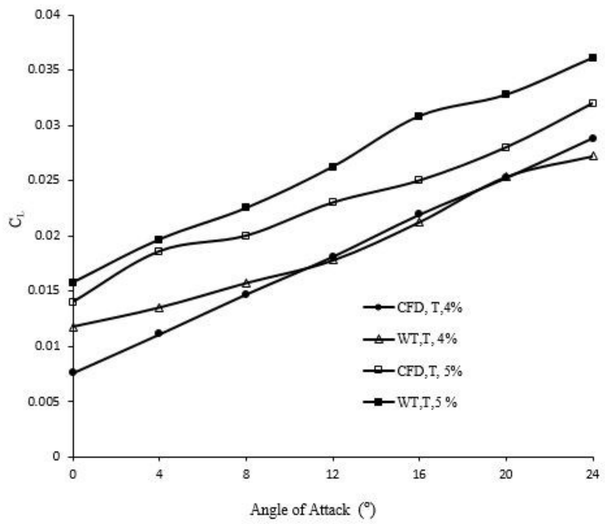


Fig. 8 Validation of lift coefficient for (a) Airfoil with 2 and 3 % Gurney flap (b) Airfoil with 2 and 3 % Gurney flap.

Square serration with 2% flap provided the best configuration of all the serrated flaps by maximizing the lift to drag ratio and remarkable reduction in drag coefficient. The closeness of the numerical simulations and wind tunnel experimental results is shown in Fig. 8.

However, as the serration shape and depth changes the flow behavior and thereby gives an opportunity to manipulate the flow field, further in-depth investigations are needed to explore the best combination of serration geometry and gurney flap with a slight change in height. It is also desirable to study the flow separation property change with respect to flap height change.

Formation of vortices around the flap makes it difficult to study the flow. There are two main vortices in every gurney flap. A vortex is formed immediately in front of the flap and a large vortex at the top of the trailing edge surface at moderate angle of attack. There is a third vortex situated under the large vortex on the suction surface of the airfoil in some cases.

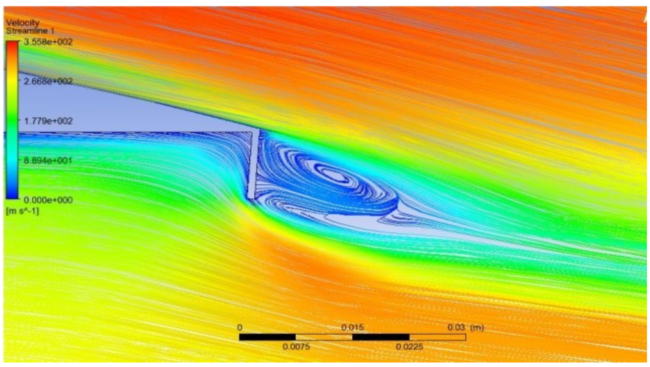


Fig. 9 Formation of two contra rotating vortices at angle of attack 4º.

This case usually happens when the flap height is as small as the thickness of the boundary layer of the flow. Increment in flap height triggers Karman Vortex Street and the flow characteristics changes abruptly and becomes unsteady as shown in Fig. 9.

4. CONCLUSIONS

In recent years there has been an increased interest in primary criteria in the design of wings include maximizing efficiency and control; thus increasing desired effects while diminishing undesired effects such as drag so that the wing becomes more functional and provides sufficient means of control. From the study, it is determined that the addition of gurney flap increase the angle of attack before stall which is nearly 15-17 degree for NACA 2412. The wind tunnel and CFD analysis confirmed that the square serration for 2% flap provides the best performance among all as a result of remaining the flap within the boundary layer thickness. The trends observed in the numerical simulations were found to agree well with available experimental results. While not all hypothesized flow features were captured behind the flap, enough of the flow disturbances caused by the application of the Gurney flap were captured for the validation of the results with experimental data. Larger gurney flap provided increased lift accompanied with drag increment. The study reveals that the lift to drag ratio is higher for square serration than triangular serration and the factor affecting the performance is the effective area of the flap.

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