Aeroacoustic and Aerodynamic Analysis of Airfoil Using Biomimicry: Serrated Trailing Edge

1 **Kshitiz Bohara**[1], 2 **Kishan Rahul Prajapati**[1], 3 **Dhruba Aryal**[1], 4 **Deepesh Darji**[1], 5 **Hari Bahadur Dura**[1]

1 Department of Mechanical Engineering, Institute of Engineering-Pulchowk Campus, Tribhuvan University, Lalitpur, Nepal

Email address:

boharakshitiz@gmail.com (K. Bohara), kishanpra111.kp@gmail.com (K.R. Prajapati), dhrubaaryal0103@gmail.com (D. Aryal), deepeshmahate@gmail.com (D. Darji), duraharis@gmail.com (H.B. Dura)

Abstract: Several attempts have been made to enhance the aerodynamic performance of an airfoil. Besides improving the lift and drag properties, the acoustic performance of an airfoil is also a significant field of consideration. This paper presents an implementation of biomimicry; serrated wings inspired by an owl in particular, on supercritical airfoil NASA SC-0714 and simulation results of different models of saw tooth serrations at different angle of attacks to obtain measurement of self-noise over trailing edge. And compares it with analytical predictions obtained by Howe. The steady-state simulation considers models with seven different serrations of different lengths and numbers. The results showed a considerable decrease in the acoustic power level from that of normal airfoil along with the aerodynamic characteristics, lift and drag. The effect of the angle of attack on acoustic power level on serrated and non-serrated airfoils was also studied. The acoustic power level was found to decrease with an increase in the angle of attack till a certain angle and then the sound power level increased drastically due to large-scale separation. The serration resulted in a lower acoustic power level for all angles of attack.

Keywords: Aeroacoustics, Self-noise, Biomimicry, Trailing edge serrations

1. Introduction

Harnessing wind energy relies upon the aerodynamic interaction of flowing wind with airfoils which also is responsible to engender noise. Airfoil, as it interacts with the flowing dynamics of air, has special aeroacoustics considerations [1]. Brooks identified different aerodynamic interactions for airfoil self-noise [2]. The noise generation mechanism of an airfoil is mainly due to self-generated airfoil turbulence scattered on the trailing edge [3]. Lighthill's analogy identified the origin of sound and defined turbulence to be the source of sound [4][5]. As convecting turbulence from within the turbulent boundary layer passes the trailing edge into the wake, noise is produced [6]. Moreover, the scattering of turbulent fluctuations near edges is found to be more significant at lower Mach numbers. [7]

It has long been recognized that airfoil trailing edge noise may be reduced by modifying the trailing edge geometry to reduce the efficiency by which vorticity is scattered into sound [8]. Retrenched aerodynamic noise from the airfoil interaction enlarges the scope for using them. Delivery of goods via quadcopters in urban areas, serrated airfoils in aircraft, wind turbines, and pantographs in high-speed trains are some areas of implementation. Since noise is directly accountable for several psychological and physical health hazards, a method to abate it bears a notable need.

Nature has been a major source of inspiration to help reduce these problems by studying the behavior of certain fishes, birds, and animals as they move through the water or air. This paper considers the reduction of aeroacoustics from airfoils by introducing trailing edge serrations; inspired by the owls. There are several features of an owl that makes it achieve silent flight. The serrated wing structure on the leading edge, the velvety material of the wings, and the fringes on the trailing edge are the main characteristics that make the owl this deadly [9].

Experiments have shown, the use of serrated trailing edges enhances the acoustic performance [10][11][12], decreases drag [13] however causes noticeable reduction in lift [14]. In this paper, we obtain the simulation results for different triangular serration models for its both acoustic and aerodynamic performances and compare them with the noise radiation predicted analytically by Howe's theory for serrated trailing edges.

2. Methodology

2.1. Design of airfoils with serration

Different types of serrations considered initially included saw-tooth, sinusoidal, wishbone and trapezoidal. Trapezoidal serration was rejected because it was less effective compared to others [3]. Wishbone serration was rejected because of the complexity of geometry and unavailability of required information. Finally, saw-tooth serrations were selected over the sinusoidal serrations because of its simplicity and higher noise reduction ability [15]. The analytical reductions in sound intensity due to saw-tooth serration for low Mach number is;

$$\text{Sound Reduction} = 10\log_{10}(1+(4h/\lambda)^2) \quad (1)$$

where ‘λ’ refers to the wavelength and ‘h’ refers to the amplitude of serrations [16][17].

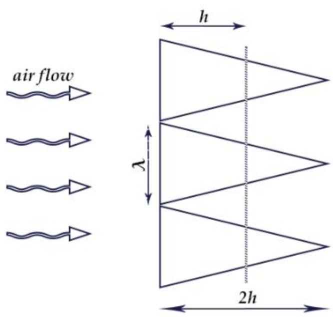

Figure 1. *Serration geometry*

NASA SC-0714 airfoil with chord length 1m and wing span of 0.2 m was used over which different serrations were made. Serrations were designed in such a way that the effective projected area in the horizontal plane made by the serrated airfoil was close to that covered by normal airfoil. Any deviation in this area could resulted in deviation in aerodynamic forces generated. So, to keep the effective area a constant factor, the serration was designed with midpoint of the length of the triangular tooth lying at the trailing edge of the wing.

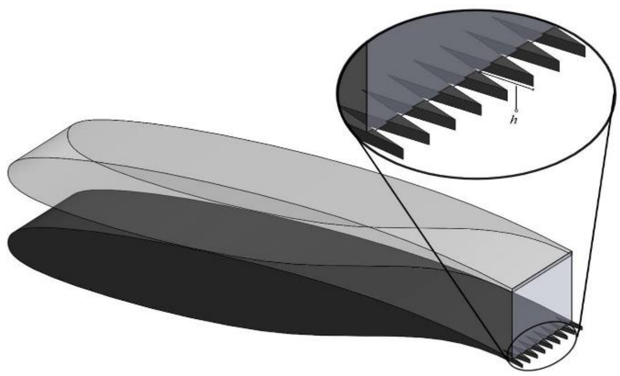

Figure 2. *Modelling of serration on airfoil. Semi length of the serration ‘h’ is extruded outward from the wing trailing edge whereas remaining half of the serration is cut into the wing.*

2.2. Case studies on serrations

Three case studies were performed to study the effect of different factors on the noise reduction by serrations. The effect of the length of serrations, number of serrations and angle of attack were studied. The choosing of the serration ratio was based on recommendations given in reference [16].

2.2.1. Effect of length of serration

In this case, the length of serrations at the trailing edge were varied and its effects were studied. The value of λ was taken 25mm (2.5% of the chord length) and the ratio λ/h was varied to change the length of the serrations. Table 1 and Figure 3 show models with different serration length.

Table 1. *Models with different serration length for λ=25mm*

Model	λ/h ratio	Length of serration (2h)
S_1	2	25mm
S_2	1	50mm
S_3	0.5	100mm
S_4	0.25	200mm

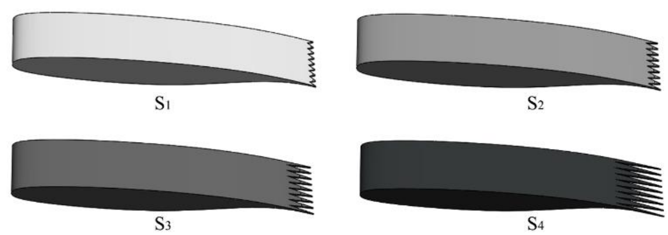

Figure 3. *Geometries with different length of serration*

2.2.2. Effect of number of serrations

In this case, the number of serrations at the trailing edge were varied and its effects were studied. The value of h was taken 25mm (2.5% of the chord length) resulting the length of serration to be 50mm. Ratio λ/h is changed to get models with different number of serrations shown in table 2 and figure 4.

Table 2. *Models with different number of serrations for h=25mm*

Model	λ/h ratio	Number of serrations	Wavelength(λ)
S_5	4	2	100mm
S_6	2	4	50mm
S_2	1	8	25mm
S_7	0.8	10	20mm

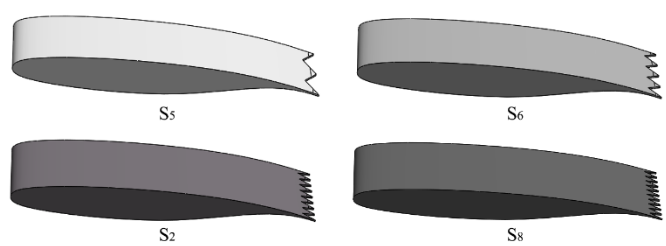

Figure 4. *Geometries with different number of serrations*

2.2.3. Effect of angle of attack

In this case, the angle attack of airfoil was varied and its effect was studied. For this study the best serration model with both acoustic and aerodynamic chacacteristics was taken to compare against the normal non serrated model. The study was initially done at 0°angle of attack and angle of attack was increased gradually until stall angle and the acoustic and aerodynamic performance of serrated and non-serrated model were compared. The study was done at angle of attacks of 0°, 5°,8°, 10° and 15°.

3. CFD Analysis

The earliest approach included setting up 2D mesh in ICEM CFD to find out the domain size which was simulated for Steadystate in ANSYS FLUENT 18.1.

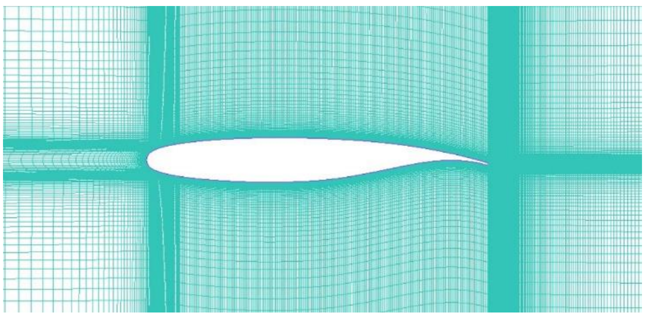

Figure 5. *Unstructured mesh for2d airfoil. Mesh resolution of first cell height of 0.0001m at the boundary of airfoil with growth ratio of 1.1 ahead of leading edge, above and below airfoil and ratio of 1.01 beyond trailing edge to yield y+ value close to 1*

Under iterative procedure, various domains with increasing distance were simulated to observe the change in acoustic power obtained from the broadband noise model. The setup parameters included main stream velocity of 50 m/s with Reynolds number 3.423×10^6. The domain size of 10 chord lengths beyond the leading edge, upper camber and lower camber and 45 chord lengths beyond the trailing edge was taken.

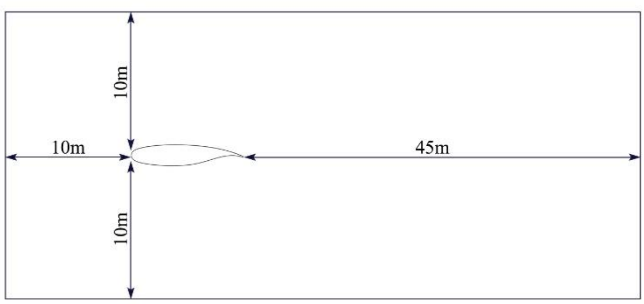

Figure 6. *Size of domain*

The domain size calculated from 2D simulation were used in 3d simulations. By analyzing the results obtained from the solution, an iterative hit and trial approach was used to keep the y+ value within the recommended limits to obtain high accuracy in results. For maintaining y+ value close to 300, the first cell height was kept to 0.003m with growth rate of 1.1 ahead of leading edge, above upper camber and below lower camber and 1.01 beyond trailing edge. Similarly, 3D models of serrated wings were also meshed in ICEM CFD.

Double precision was used to get more accurate results in simulation. Pressure based solver was selected as the simulation was done in incompressible flow. Realizable k-ε turbulence model was selected because it is suitable for phenomena like boundary layer separation and vortex shedding. Second order upwind discretization was chosen for its higher accuracy. Broadband noise model was chosen as it only requires steady state simulation and it offers acoustic power level data all over the numerical domain showing where noise is being produced and at what level.

The domain for 3D wing was created by extruding the 2D domain in span wise direction such that the planes of the domain were in contact with the airfoil sections of the wing. These two planes were treated as symmetry during simulation making wing an infinite wing.

Ansys Fluent has two models for acoustic simulation. FW-H model and Broadband noise model. Broadband model is chosen for steady flow simulation. The velocity inlet of 50m/s was designated at inlet which resulted in the Reynold's number of 3.423×10^6. The outlet was set up as pressure outlet with gauge pressure of zero Pascal based upon the outflow condition. The two walls were set up at specified shear condition of zero shear so that there is no formation of boundary layer. The temperature and pressure were kept at standard atmospheric condition. The standard value of 10^{-12} Watt was used for the reference acoustic power.

4. Results and Discussion

2D simulation results were used as test beds to carry out the 3D simulation. The domain size calculated from 2D simulation was used for the 3D simulations.

4.1. Results for effect of length of serrations

For the first case study the effect of length of serrations at the trailing edge of the airfoil were studied. For that four serrations of different lengths were modelled in Solidworks 2018. The results of the four serrations of different length are compared with non-serrated airfoil. The results obtained are shown in table 3. The table shows the values of lift coefficient, drag coefficient and sound power level for different serration models along with non-serrated model.

Table 3. *Results for effect of length of serrations*

Model	Ratio (λ/h)	Length of serration (2h)	Lift coefficient	Drag coefficient	Sound Power Level (dB)
S_0	n/a	n/a	0.51804	0.014747	93.68929
S_1	2	25	0.46631	0.016292	85.73691
S_2	1	50	0.44936	0.014473	81.64606
S	0.5	100	0.35816	0.015545	78.27835
S_4	0.25	200	0.22714	0.015618	89.45120

The sound reduction according to Howe's model is calculated and then compared with simulation results. From the graph below shown in figure 7, it can be seen that results obtained from the simulation does match with Howe's model except for the model S_4 with λ/h ratio 0.25. The maximum sound reduction is obtained for model S_3 with λ/h ratio 0.5 of 15.41094dB. The serrations on the trailing edge does affect the aerodynamic properties of the airfoil causing the decrease in the lift of an airfoil. The lift coefficient decreases with the decrease in the λ/h ratio. The drag coefficient however doesn't follow any pattern and model S_2 with λ/h ratio 1 produces even less drag than non-serrated airfoil. So, from this study it showed the higher reduction in sound and lift coefficient with reduction in λ/h ratio i.e. increase in the length of serration. Considering all the properties including lift coefficient, drag coefficient and sound reduction the model S_2 with λ/h ratio 1 produces the best result.

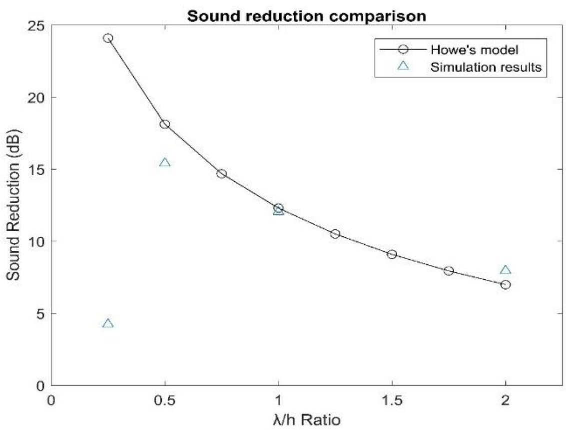

Figure 7. *Comparison of sound reduction for different length of serrations with Howe's model*

The contours of acoustic power level for models S_0 and S_3 are also shown below in figure 8 and figure 9 respectively. The contours show that the maximum sound power level is at the trailing edge of wing. For non-serrated airfoil there is maximum sound power level of 93.7 dB and for model S_3, the maximum sound power level is 78.3 dB

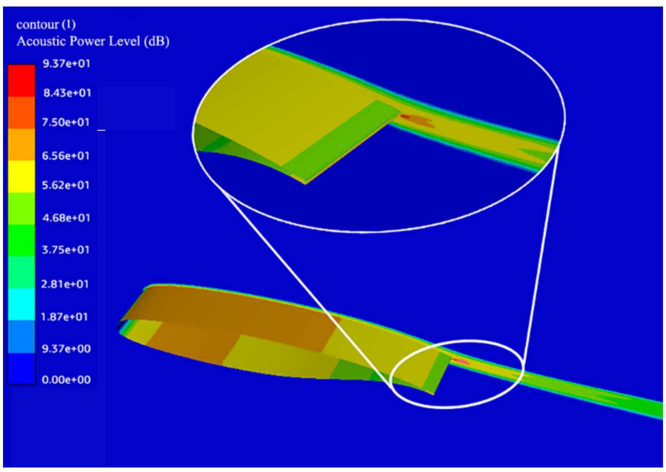

Figure 8. *Contours of acoustic power level for non-serrated airfoil S_0*

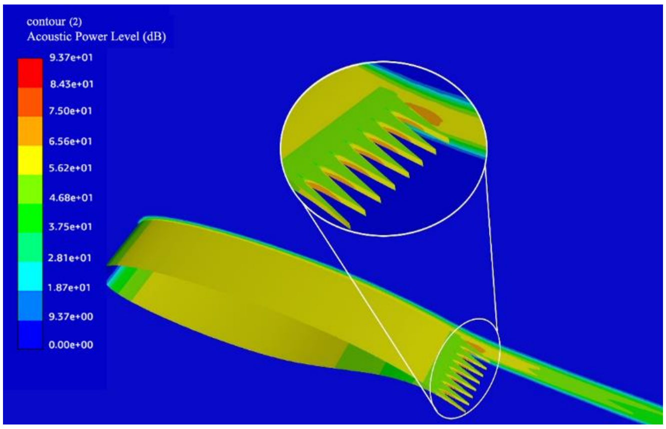

Figure 9. *Contours of acoustic power level for serrated model S_3*

4.2. Results for effect of number of serrations

For second case study effect of number of serrations at the trailing edge were studied. The result of four models with different number of serrations are compared with non-serrated airfoil. Results obtained are shown below in table 4.

Table 4. *Results for effect of number of serrations*

Model	λ/h ratio	Number of serrations	Lift coefficient	Drag coefficient	Sound Power Level (dB)
S_0	n/a	n/a	0.51804	0.014747	93.68929
S_5	4	2	0.46905	0.014490	91.60948
S_6	2	4	0.45504	0.014620	87.48469
S_2	1	8	0.44936	0.014473	81.64606
S_7	0.8	10	0.44319	0.014333	86.30137

Graph shown in figure 8 shows sound reduction comparison with Howe's model. Simulated result follows Howe's model except for model S_7. Sound reduction increases with increases in number of serrations. The value of lift coefficient also decreases with increase in number of serrations. Drag coefficient has been found to be lower for serrated airfoil. From this study the model with best result is the model S_2.

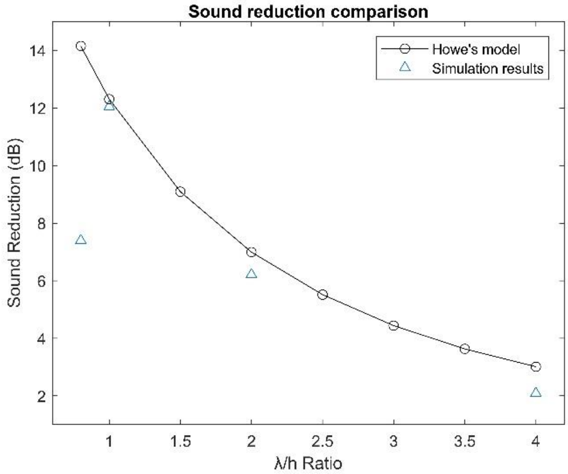

Figure 10. *Comparison of sound reduction for different number of serrations with Howe's model*

Figure 11 shows acoustic power level for model S_2 with maximum sound power level of 81.6 dB at trailing edge.

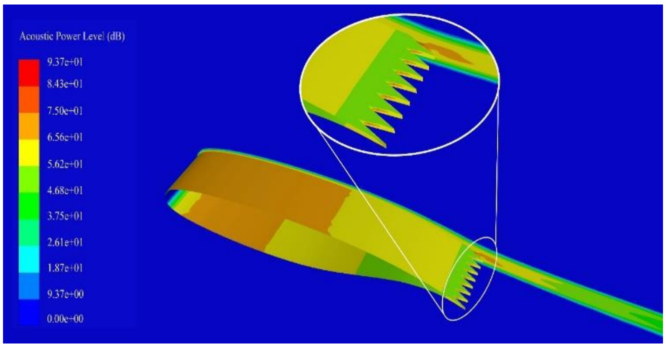

Figure 11. *Contours of acoustic power level for model S_2*

4.3. Results for effect of angle of attack

Effect of different angle of attack was studied for non-serrated airfoil and serrated model S_2(because of its better aeroacoustics and aerodynamic performance) Results obtained are provided in table 5 and 6 respectively.

Table 5. *Results of simulation for non-serrated airfoil at different AOA*

Angle of attack	Lift coefficient	Drag coefficient	Sound power level(dB)
0°	0.51804	0.014747	93.68929
5°	1.0382	0.024548	89.48789
8°	1.3004	0.035836	86.18059
10°	1.4397	0.046467	89.28711
15°	1.5435	0.11757	109.0693

Table 6. *Results of simulation for serrated airfoil S_2 at different AOA*

Angle of attack	Lift coefficient	Drag coefficient	Sound power level(dB)
0°	0.44415	0.014403	81.64606
5°	0.96439	0.023070	80.64074
8°	1.2378	0.033333	85.13443
10°	1.3890	0.043200	88.29211
15°	1.4817	0.091732	96.46183

Graph shown in figure 12 shows the sound power level at the different angle of attacks for modelS$_2$.

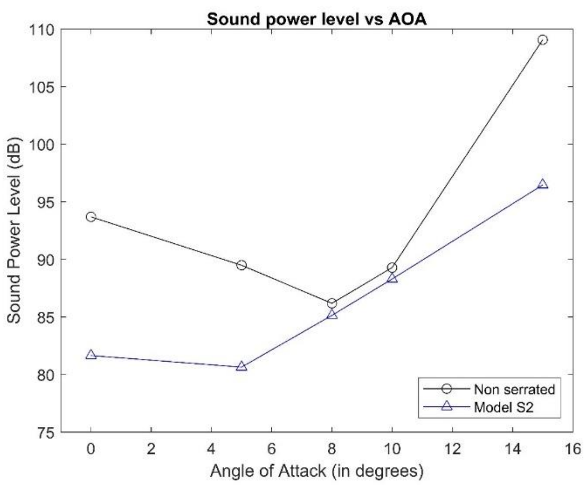

Figure 12. *Graph showing sound generated at different AOA*

The graph shows reduction in sound power level with increase in angle of attack up to certain angle of attack for both serrated and non-serrated airfoil. Then further increase in the angle of attack causes increase in sound power level. This is because of the sound produced due to large-scale separation at higher angle of attack. It is also found that the sound power level of the serrated airfoil is less than that of non-serrated airfoil at all angle of attacks.

On comparing the lift generated at different angles for the serrated model S_2 with serrated model S_0 shown by figure 13, serrated model has coefficient of lift lower than the non-serrated model for all angle of attack. There is lift decrement of about 14% compared to normal airfoil at 0° angle of attack compared to the normal airfoil. Similarly, at 5°, 8°, 10°and 15° angle of attack there is lift decrement of about 7 %, 5%, 3.5%, and 4% respectively.

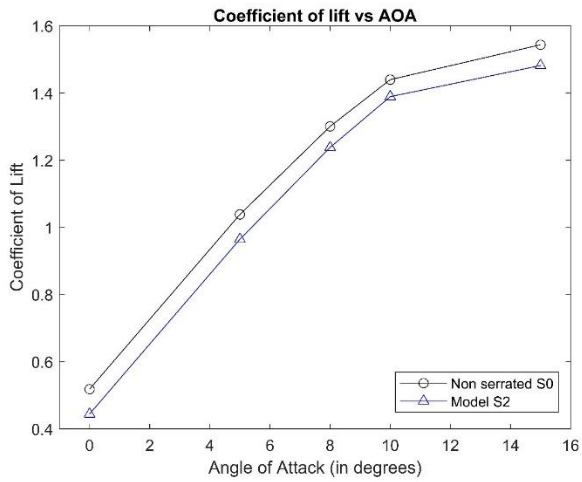

Figure 13. *Graph showing coefficient of lift at different AOA*

Likewise, figure 14 shows coefficient of drag at different angles of attack for both serrated model S_2 and non-serrated model S_0. In the graph, coefficient of drag for serrated model is seen to be lower than non-serrated model for every angle of attack.

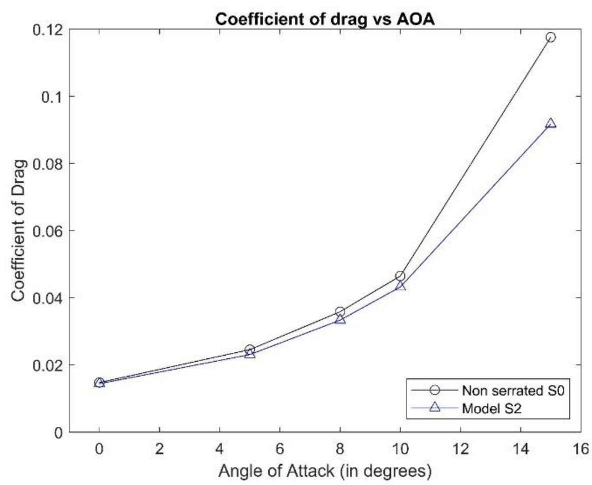

Figure 14. *Graph showing coefficient of drag at different AOA*

5. Conclusion

This paper illustrates the effect of different length and numbers of the serrations at trailing edge over aero acoustic and aerodynamic characteristics of airfoil NASA SC-0714. The analysis of the results concluded that sound reduction increased with increase in length as well as increase in number of serrations. But the serrations also decreased the lift coefficient of airfoil with increase in length and number of serrations. Considering the aerodynamic performance along with noise reducing capability the serration model S_2 with λ/h ratio equal to one with 8 serrations on 0.2m span (λ =25mm is span wise length of serration and 2h=50mm is root to tip length of serration) produced best results. This model produced sound reduction of 12dB and better lift and drag coefficient compared to others. This serrated airfoil caused lift decrement of about 14 % at different angle of attacks. Similarly, study effect of angle of attack on noise production concluded that noise generation decreased slightly with increase in AOA up to certain angle and increased drastically with further increase in AOA due to large scale separation. The study also concluded that serrations are effective at all AOA.

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