AIP Conference Proceedings

RESEARCH ARTICLE | FEBRUARY 16 2021

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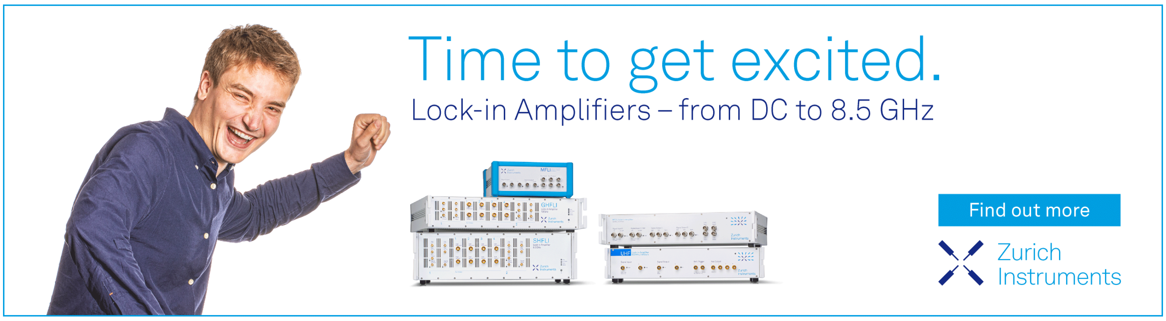
AIP Conference Proceedings 2316, 020011 (2021)
https://doi.org/10.1063/5.0036694



Aerodynamic Optimization Study on Transport Aircraft Wing

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Abstract

Conceptual and preliminary stages of aircraft design require significantly large number of simulations for performance analysis. As the design involves aerodynamics, structural dynamics, propulsion and controls, the number of parameters involved is considerably high. It will be time consuming to simulate various cases for analysis and design optimization. A surrogate model constructed based on few parameter sets based on Design Design of Experiments (DoEs) is quite helpful to analyse the influence of different parameters in the design space. It also helps to arrive at optimum design. The process of surrogate model development and optimization based on use of Genetic Algorithm on the surrogate model is considered in this study for the aerodynamic design of transport aircraft wing, before extending this method to include other disciplines.

The Common Research Model (CRM) wing of NASA has been taken as baseline model. It has a sweep of 35°, and a maximum airfoil (t/c) of 0.1542, 0.1052 and 0.095 at root, Yehudi break and tip respectively. The design Mach number is 0.85.

The design space considered in this work a) variation of Mach number from 0.75 to 0.85, b) sweep of 29° to 38°, and c) maximum t/c ratio difference of 4 % to 12% variation from baseline wing was considered in this study. The geometric model of the wing was constructed using the CATIA software. The mesh was generated with ICEM CFD software. The CFD simulation of baseline model was carried out using open domain software SU2 with RANS and Euler approaches. ANSYS Fluent software was also used to verify the results obtained from SU2 software.

The surrogate surface was constructed for the three-design variable with the help of Kriging method. The influence of the design parameter on $C_{L,}$ C_D and C_L/C_D was analysed. A genetic algorithm available in MATLAB was used to identify the optimum design. The predicted optimum wing configuration was again simulated to verify the confidence in the design.

Keywords: Mach number, maximum airfoil thickness to chord ratio (t/c), wing sweep, surrogate model and Optimization

1. INTRODUCTION

Any new design of an aircraft involves different phases, namely requirements definition, conceptual design, preliminary design and detail design. In the initial stages the requirements

Advanced Trends in Mechanical and Aerospace Engineering
AIP Conf. Proc. 2316, 020011-1–020011-10; https://doi.org/10.1063/5.0036694
Published by AIP Publishing. 978-0-7354-4059-3/$30.00

definition is necessary to identify the key requirement for designing the aircraft through a feasibility analysis. In conceptual design phase, various configuration of aircraft is evolved through discussions, simple design calculations and design charts by studying the effects of aircraft parameters such as thrust to weigh ratio, wing loading, aspect ratio etc. In fixed wing transport aircraft, the wing design plays an important role on the overall performance of the aircraft. The proper selection of airfoil, wing planform area, taper ratio, aspect ratio, sweep, thickness to chord ratio (t/c) is important to provide maximum (C_L/C_D). The C_L and C_D was estimated based on airfoil category, lower order models such as panel code and vortex lattice methods. Currently, simple design tools such as JavaFoil, XFoil, OpenVSP and other tools are available for low fidelity analysis. These tools are helpful to perform many calculations within less computational time. However, these tools may not predict well in the transonic region. Mostly, Euler and Navier-Stokes calculations are more accurate with increasing in computational cost respectively. Since, the transport aircrafts flies at transonic region during most of the cruise conditions, Euler calculation are considered to be reasonable for the present computing power and developments in computational methods.

It is also important to perform parametric study and analyse the results for better wing configuration during the initial stages of preliminary design phases. The multi-disciplinary design of aerodynamics, structures, propulsion and aero-elasticity is the main activity in the preliminary design. Before getting into Multi-disciplinary Design Analysis and Optimization (MDAO), aerodynamic optimization of a wing was considered in this study.

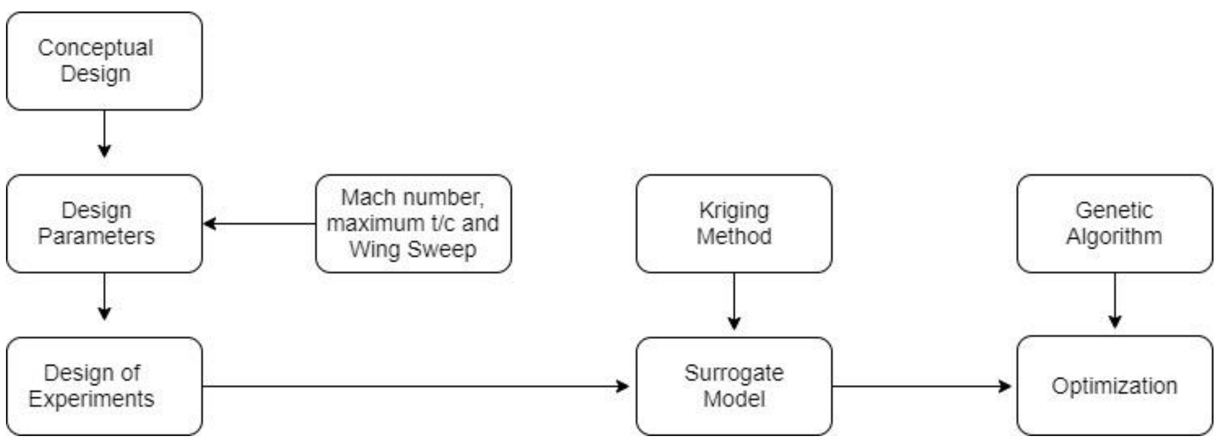

FIGURE 1. Flow chart for aerodynamic optimization of a wing

A well-known NASA Common Research Model (CRM) transport aircraft wing alone was considered in this study. The complexity in the wing geometry due to twist distribution along the span and Yehudi break make it more advanced wing. The wing parameter of (t/c) and sweep was varied along with flight Mach number. The inviscid calculations were performed with SU2 code. The surrogate model for this design parameter was created with Kriging methods. The genetic algorithm was used in the design optimization process. The framework of the process is shown in Fig. 1. This study describes a systematic approach on arriving optimal parameters.

2. METHODS AND METHODOLOGY

In this section the details of CAD modeling, grid generation, boundary conditions, flow solver, surrogate modeling and optimization procedure are discussed. It is to arrive the optimum solution from the baseline model. It also analyzes the solution for the given parameters in the design space.

2.1 CAD modelling, Grid Generation and Boundary Conditions for CRM Wing

NASA CRM is a modern aircraft configuration that was designed as an open geometry for aerodynamic prediction and validation of a transport aircraft with cruise Mach number of 0.85. [8] The CRM wing has a reference area of 383.6 m^2, span 58.7 m and aspect ratio 9. The CRM wing was developed with airfoil CRM.65 with the blunt trailing edge. The wing has Yehudi break at 37 % of the semi-span. It has maximum t/c at wing root, Yehudi and tip 0.152, 0.1052 and 0.095 respectively. Also, it has taper ratio of 0.275 and mean aerodynamic chord of 7.0 m.

In order to construct the geometric model of CRM wing, CATIA software was used. Initially airfoils were placed at the wing root, Yehudi and tip locations and surface was created. The surface model of CRM wing is shown in Fig. 2.

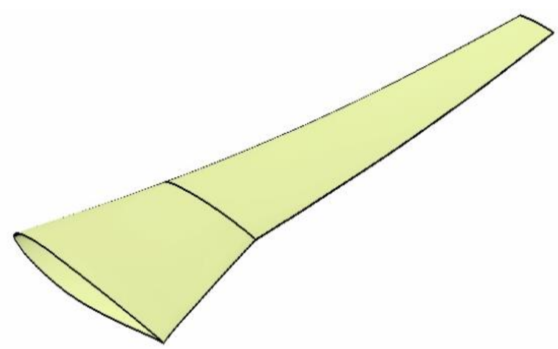

FIGURE 2: CRM Wing Geometry

The unstructured grid was generated in ICEM -CFD software. The flow domain was created by considering leading edge of root airfoil as reference point. The size of the domain was selected as 10 times the root chord ahead of reference point and 20 times the root chord behind the reference point to provide appropriate boundary conditions and also to capture the flow along the wing geometry. The unstructured grid was generated by varying the cell size. In order to capture smooth flow near the wing tip and trailing edge the grid size was kept 10 and 4 points respectively. Finally, the fine mesh was created with about 3 million elements count.

The CFD analysis for the wing model was carried out using open domain software SU2 and further few cases was verified using ANSYS Fluent. The following boundary conditions were used:

- Symmetry boundary condition on the domain surface at the wing root section.
- Pressure far field in the spanwise and chordwise domain boundaries.
- No slip boundary condition on the wing surface.
- Pressure was prescribed at the outlet

The operating conditions used for the CFD analysis to evaluate the aerodynamic performance of baseline model was Mach number of 0.85, static pressure of 201326.9 of Pa, temperature 310.96 of K and Reynolds number 5 million [8].

2.2 Stanford University Unstructured (SU2) Flow Solver

SU2 is an open source design and analysis software for solving the complex and multidisciplinary problems. The software is built with collection of C++ modules at its core that are linked within the python framework to perform the computations to solve of partial differential equations associated with the problems [2]. In this study the SU2 tool was chosen to perform the aerodynamic analysis because of its abilities and its availability. Computational time and cost involved in SU2 analysis are affordable.

2.3 Kriging based Surrogate Modeling and Genetic Optimization

Kriging is an interpolation technique which considers both the distance and the degree of variation between the data points to estimate unknown areas. It is also called as Gaussian process regression. It allows the user to derive weight that results in unbiased estimates. Initially, experiments/simulations are conducted at sample points. The sample points are chosen at maximum value, minimum and equal interval values. For example, the Mach number was varied as 0.75, 0.80 and 0.85. The Kriging method tries to give minimum error at the sample points. Over the surrogate surface, the genetic algorithm is used to obtain the maximum values of CL/CD. The MATLAB tool has genetic algorithm to optimize the given function with the range of variables, population size, mutation, crossover and total number of equations.

3. RESULTS AND DISCUSSION

For the optimization of wing, it is necessary to validate the baseline model first. The CFD analysis for baseline wing model was carried out using Euler and RANS approaches. The turbulence model used for viscous analysis was Spalart-Allmaras (S-A). The operating conditions of Mach number, pressure and temperature used in this simulation was already mentioned in the section 2.1.

3.1 Validation of Baseline Model

The CFD analysis was made for different angles of attacks to see its effect on C_L/C_D ratio.

TABLE 1. Comparison of C_L and C_D between Fluent and SU2 (Euler approach)

	Fluent			SU2		
AOA	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D
1.5˚	0.48	0.013	36.92	0.52	0.013	40
2.37˚	0.56	0.020	28	0.60	0.022	27.27
3.06˚	0.68	0.031	21.94	0.75	0.033	22.72
5˚	0.92	0.077	11.95	1.01	0.082	12.32

Table 1 shows the comparison of CL/CD results between Fluent and SU2 for Euler approach. It can be seen that as the angle of attack increases the coefficient of lift and drag values also increases. The C_L/C_D ratio decreases, as the coefficient of drag becomes more dominant, with the increase in angle of attack.

Similarly, RANS simulations were made to analyze the effect of viscosity of flow over the wing. Here the same operating conditions were used as that of Euler approach. The results are shown in Table 2. It is seen that the value of coefficient of lift is decreased when compared to inviscid approach as the effect of skin friction drag is also considered in viscous flow. The C_L/C_D ratio is almost decreased by 12 % due to viscous effect.

TABLE 2. Comparison of C_L and C_D between Fluent and SU2 (RANS approach)

	Fluent			SU2		
AOA	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D
1.5°	0.39	0.015	26	0.41	0.015	27.34
2.37°	0.49	0.026	18.85	0.52	0.027	19.26
3.06°	0.57	0.045	12.67	0.61	0.049	12.45
5°	0.78	0.08	9.75	0.84	0.082	10.24

The SU2 results shows good agreement with the Fluent results as seen in Table 2. The SU2 solver is further used to simulate various cases for the optimization.

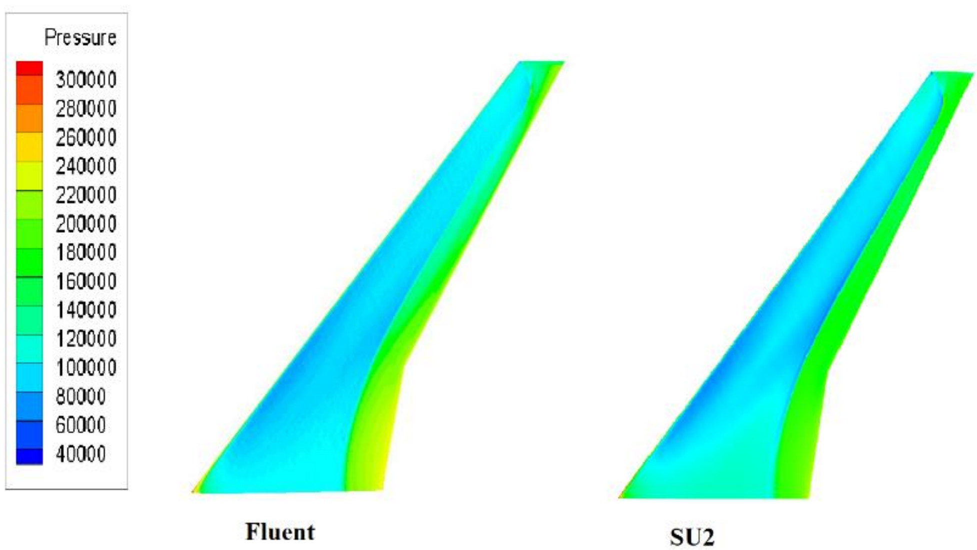

FIGURE 3. Contour of pressure over upper surface

Figure 3 shows contour of pressure at 2.37° angle of attack. The pressure decreases near the leading edge as the flow expands where, the velocity to be more. As the flow takes places along the wing surface, the pressure increases due to the presence of shocks. It is also noticed that pressure increases near wing tip. The shock wave is seen at about 80 % chord location of airfoil, throughout the span and turns near the tip.

Figure 4 shows contours of Mach at 2.37° angle of attack. It clearly shows the supersonic and subsonic regions. The shock structure predicted from SU2 and ANSYS shown similar structure. This comparison ensures that the implementation of the problem in SU2 is consistent.

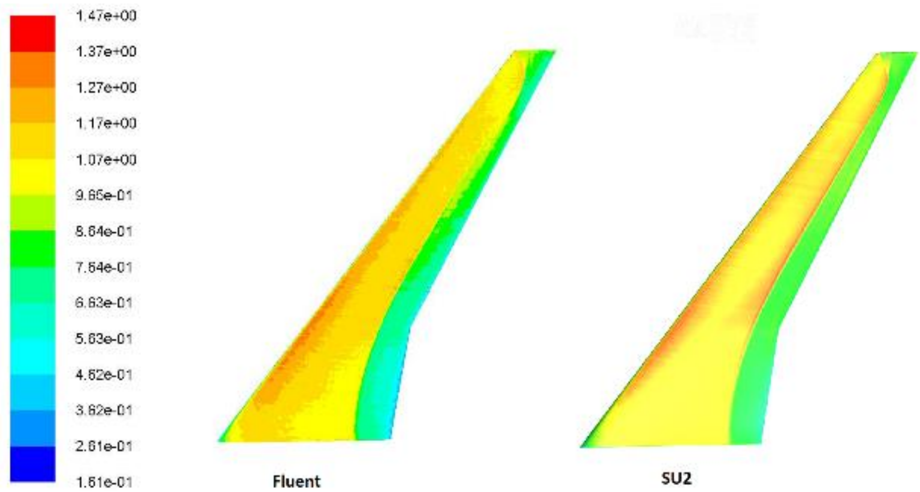

FIGURE 4. Contour of Mach number plot upper surface

Figure 5 shows coefficient of pressure distribution over the wing from leading edge to trailing edge at a location of 8 m span from the root of the wing. C_P is plotted upside down with negative values (suction) above the x-axis. The flow expands at the leading edge and pressure variation takes places both on upper and lower surfaces and finally leaves through the trailing edge. On the upper surface, the low pressure is maintained till 80 % of the chord and then increases due to the presence of the shock.

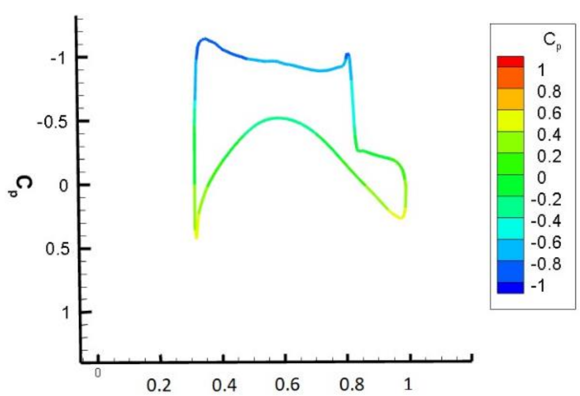

FIGURE 5. C_P curve at span of 8m

3.2 Design of Experiments (DoE)

Optimization of wing has become a regular feature with availability of computational facilities. Out of various combination parameters available for optimization, in this study we have chosen wing sweep, maximum airfoil thickness to chord ratio and Mach number as key parameters for optimization. The wing sweep was varied between 29° to 38°, maximum airfoil thickness to chord ratio varied between 4 to 12% and Mach number between 0.75 to 0.85. Totally 12 different geometries were created by varying the wing sweep and thickness to chord ratio. For the CFD analysis of these variation of parameters, only the Euler approach was considered from time considerations. It also served as a replacement for 'low fidelity 'codes like panel or vortex lattice methods.

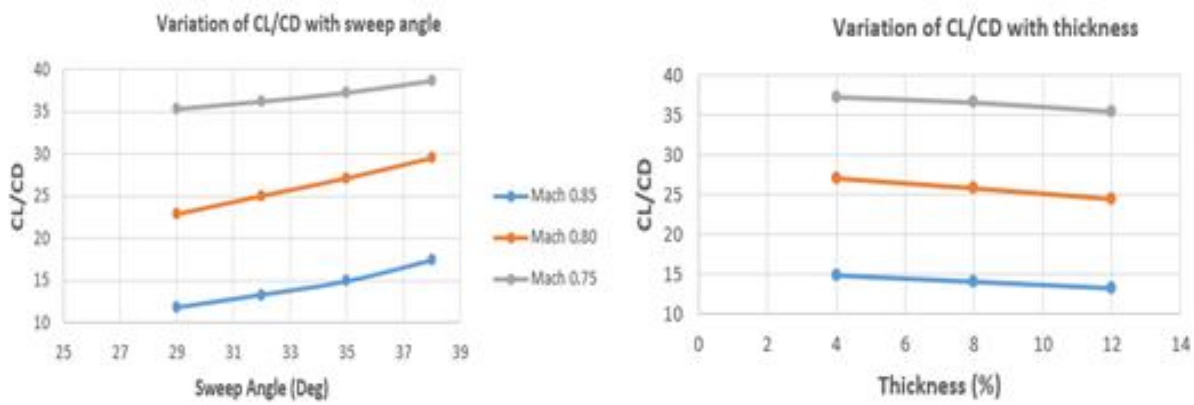

FIGURE 6. Variation of CL/CD with Sweep angle and Maximum airfoil thickness to chord ratio

As the sweep angle increase the C_L value decreases but also at transonic flow condition the C_D value also decreases [7]. From Figure 6 it can be seen that as the sweep angle increase the C_L/C_D ratio also increase. Also, as the Mach number increases the C_L/C_D increases. Figure 6 shows variation of C_L/C_D with the change in maximum airfoil thickness. As the thickness of the airfoil increases the C_D value increases which in turn results in decrease in C_L value. Also, as the Mach number increases the C_L/C_D ratio also increases.

3.3 Surrogate Surface

The Kriging based surrogate surface was designed using the optimization results for combination of wing sweep, maximum airfoil thickness to chord ratio and Mach number. The results based on Kriging method is shown in Fig. 7.

Figure. 7(a) shows the variation of C_L/C_D with Mach number and maximum thickness to chord ratio for sweep angle of 35º. The Mach number has more effect on C_L/C_D ratio than the increase in maximum (t/c) percentage. At Mach number of 0.85 and increase in 4% of t/c ratio the wing gives C_L/C_D ratio of about 32. Similarly, from Fig. 7(b), at 38° sweep and increase in 4% of maximum t/c ratio has more effect on C_L/C_D ratio for mach number of 0.85. From the Fig. 7(c) for initial maximum thickness to chord ratio as mentioned in section 2.1, the wing gives maximum C_L/C_D ratio of 38.91 for sweep angle of 38º.

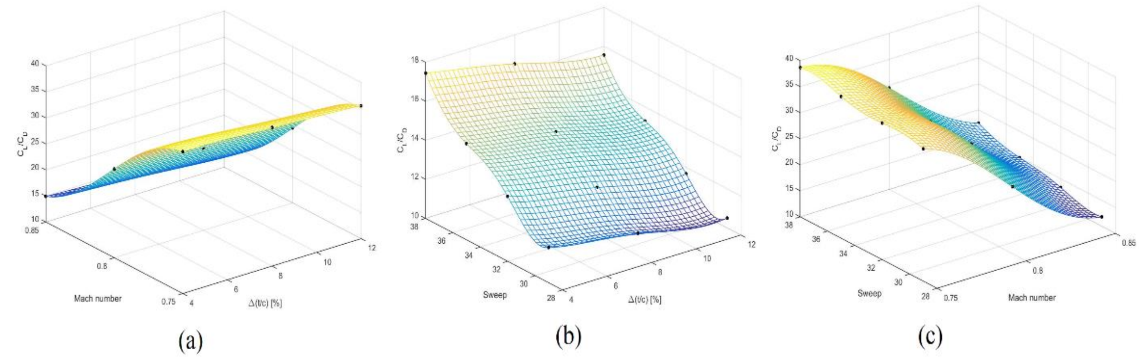

FIGURE 7. Surrogate Model

3.4 Optimization

Genetic algorithm tool available in MATLAB was used on this surrogate to predict an optimum combination of sweep, maximum airfoil thickness to chord ratio and Mach number to obtain highest lift-drag ratio (C_L/C_D). The surrogate model predicted that with increase in maximum airfoil thickness to chord ratio by 4.7 %, at Mach number 0.751 and with sweep angle of 37.32° the wing model gives maximum C_L/C_D ratio of 38.91.

TABLE 3. Comparison of Baseline and Surrogate model predictions results

	Mach number	Δ(t/c)	Sweep	CL/CD
Baseline Case	0.85	0	35 °	27.27
Predicted results using Surrogate model	0.751	4.7 %	37 °	38.91

TABLE 4. Comparison of predicted and obtained optimized results

Angle of Attack	Parameter	Predicted results using Surrogate model	Verified results for optimized design parameters using SU2	Error (%)
2.37 °	C_L/C_D	38.91	38.10	2

Using the predicted optimum combination of parameters, the wing was designed and SU2 analysis was made using Euler approach. The Table 4 shows the comparison of C_L/C_D value between predicted and SU2 analysis.

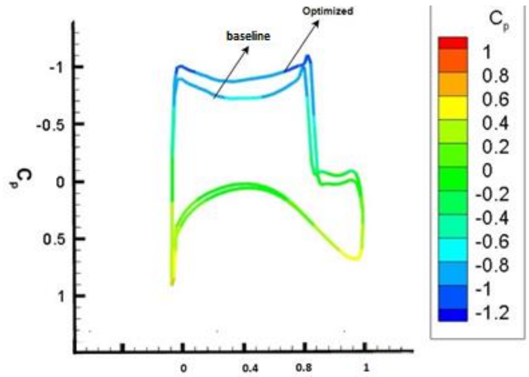

FIGURE 8. Comparison of baseline and optimized wing cp curves

Figure. 8 shows the pressure distribution over the optimal and baseline wing model. From the C_P plot we can see that the change in the thickness of the wing was the major contribution for the improvement in the coefficient of lift. The suction peak of the optimal wing was more when compared to baseline and the improvement in the C_L is due to the suction surface.

4. CONCLUSION

Optimization was carried out for NASA CRM wing model by varying the wing sweep, maximum airfoil thickness to chord ratio and Mach number. SU2 analysis was carried out using Euler approach for different combination of parameters. The optimization results showed that for any thickness value C_L/C_D ratio decreases with the increase in Mach number. For any increase in sweep angle C_L/C_D ratio increases with increase in Mach number. Genetic Algorithm (GA) tool within MATLAB program using kriging method predicted that at sweep angle 37.328°, maximum thickness to chord ratio increased by 4.676 % and Mach number 0.751 the CRM wing gives better aerodynamic performance with C_L/C_D ratio 38.91. Further, using the predicted results the CRM wing model was developed and SU2 analysis was made. The results showed that the wing generates C_L 0.54 and C_D 0.014 with C_L/C_D ratio of 38.10.

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