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IMPROVING AERODYNAMIC PERFORMANCE OF A WING USING CFD BASED PARAMETRIC OPTIMIZATION METHOD

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ABSTRACT

In this study a typical symmetric profiled wing, Onera M6's planform has been optimized by the response surface method. The objective is to maximize CL and minimize CD, while keeping the critical angle of attack above 10 degree. Optimization parameters are selected as sweep angle, taper ratio and root chord. Aerodynamic coefficients are obtained by the Computational Fluid Dynamics method and isolated wing model is used during the optimization. Response Surface Method is used in this parametric optimization study and the optimized design are obtained by using 30 Design Points whose critical angle of attacks obtained by evaluating every angle of attack of Design Points starting from 0 degree to up to 20 degree increasing by 1 degree. The effect of the wing planform parameters on aerodynamic coefficients are studied and discussed in detail. As a result of the study, wing planform is optimized to achieve 5% decrease and 3% increase in C_D and C_L, respectively, at the critical angle of attack value of above 10 degree.

INTRODUCTION

Wings are the most important component of the aircraft as a carrier surface. While the wing employs lift, at the same time, it is the major source of drag, responsible for around 2/3 of the total drag of the aircraft [Raymer, 2006]. Reducing the wing drag by a better design, and, hence, minimizing the operational cost, is often one of the primary objectives of modern aircraft design [Jonsson, Leiffsson and Koziel 2012].

Furthermore, aerodynamic optimization is by nature, a multi-objective problem but in many cases only one specific objective, such as minimization of the coefficient of drag, is selected, while the other parameters, such as the coefficient of lift is kept constant through design constraints [Leifsson and Koziel, 2011]. However, this is not convenient for some cases, since it may be necessary to understand the characteristics of conflicting objectives in a desing process. For this cases, multi-objective optimization is used.

On the other hand, in the optimization phase, what is expected from the analysis tool is that it will give a result as fast as possible and as accurate as possible [Sadraey, 2012]. In this context optimum mesh must be selected in order to reduce the number of evaluations of expensive

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simulations, thereby making the design process more efficient. Also for design space must be established with well structured constraints.

Finally, different wing geometries are used in both aviation and space applications, and it is understood that various optimization studies have been carried out to maximize aerodynamic performance by changing the wing planforms without changing the wing profile. As a result of various optimization studies using different methods for the ONERA M6 wing: By applying the single-objective genetic algorithm optimization method coefficient of drag was reduced by 10.7% while coefficient of lift was kept constant at 0.25 [Zhang, Chen and Khalid, 2003]. Also coefficient of drag minimization study was carried out for ONERA-M6 wings using the Surrogate Models, and the coefficient of drag was reduced by 24.44% [Liu, Song, Han and Zhang, 2016] and the design time and cost for the ONERA M6 wing reduction study was also carried out by using the parallelized design optimization method [Lee, Kim, Kim and Rho, 2002].

However, it was determined from the literature survey in the optimization studies for ONERA M6 the critical angle of attack which is also defined as stall angle was not taken as a constraint and evaluated since it requires excessive amount of computational afford which resulted because in the case of critical angle of attack determination, every Design Point in the optimization study has to be studied from 0 degree to the each Design Points critical angle of attack. In order to fill the gap in literature, wing planform optimized in terms of sweep angle, taper ratio and root chord and coefficient of drag reduction coefficient of lift escalation has been studied while the critical angle of attack value is held above 10 degree

METHOD

CFD Model

In this study, Onera M6 wing profile has been used. Vortex effects are neglected in design space scanning. Accordingly, a hemispherical flow volume was formed around the isolated wing as shown in Figure 1. The zx-plane of the hemisphere is defined by the symmetry boundary condition. The wing surfaces are selected as "no slip" walls and the remaining surface of the hemisphere is represented by the "pressure farfield" boundary condition. Flow velocity (accordingly, Mach and Reynolds numbers) and direction are defined relative to the wing surface to the outer surface of the hemisphere.

For the analysis ANSYS FLUENT [Ansys Inc., 2019] pressure based coupled solver has been used. SST k-w Turbulence Model [Borisov, 1995] was used for the turbulence model. Second order upwind method was used in discretization of RANS equations. The ideal gas condition is used for the state equation, and the Sutherland law is used for the viscosity-temperature relationship. The mesh is formed by prism in the boundary layer and tetrahedral elements in the remaining volume. The boundary layer mesh was created with the Last Aspect Ratio method, using 25 layers to leave the average y + value below 1 in all conditions. Computational domain and boundary condition information are given in Figure 1 and Table 1, respectively.

In optimization study flow speed is determined as 0.3 Mach and in order to obtain the critical angle of attack, all design space was studied from 0 up to 20 degrees angle of attack, increasing by one degree.

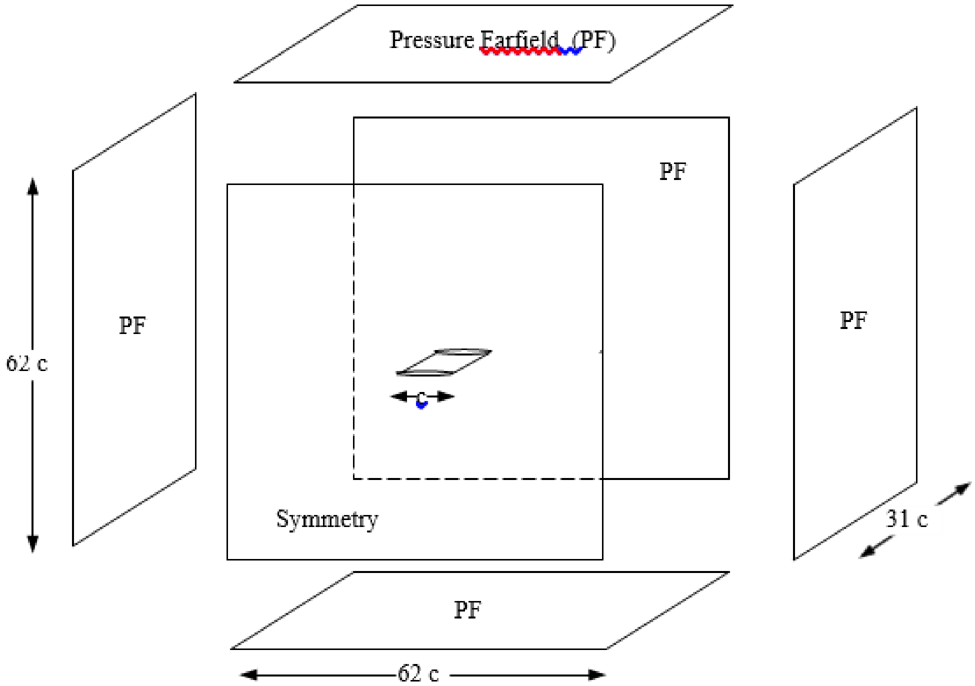

Figure 1: Flow Volume and Volume Values by Root Chord (All boundaries are set as pressure-farfield (PF), a side from the wing surface, which is a wall type. Symmetry is applied through the wing center. The wing root chord length is denoted by c.)

Table 1. Details of the boundary conditions

Surface Name	Boundary Type	Parameter	Value For Mesh Independece	Value For Optimization
Inlet	Pressure Far Field	Velociy (mach)	0.84	0.3
		Turbulence Intensity (%)	0.1	0.1
Wall	Wall	No Slip	-	
Symmetry Plane	Symmetry	-	-	

Design Space

In an optimization process, Onera M6 wing desing is used as a baseline. For this model three geometric parameter (λ, c_r and Λ) has been parameterized (Figure 3). Wing planform area has been fixed to an identical value for the design space in order to compare aerodynamic coefficients. The geometric parameters used in the design space are given in Figure 3 and the limit values of these parameters are given in Table 2.

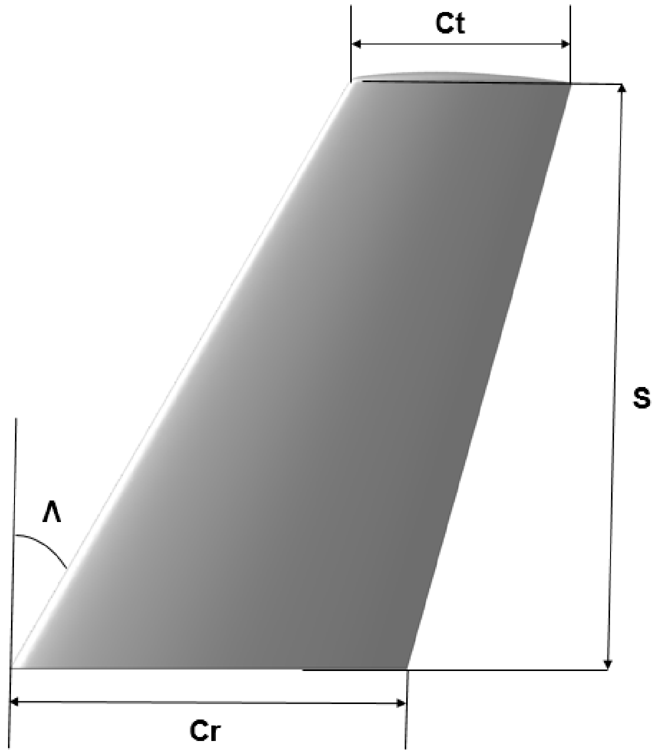

Figure 2*:* Control Surface Geometric Parameters

Table 2: Geometric Parametes Ranges Used in Optimization

Parameters	**Minimum**	**Maximum**
Sweep Angle (Λ)	10 Degree	50 Degree
Taper Ratio (Ct//Cr)	0.3	1
Root Chord (Cr)	0.4	1

In the creation of the optimization scheme, the "Face Centered Composite (FCC)" design method, which covers the endpoints of the design space, has been adopted. [Cesur and Dikbaş, 2020] The distribution of the design points of this scheme is given in Figure 1 [Ren, Heo, Kim and Cheong, 2013].

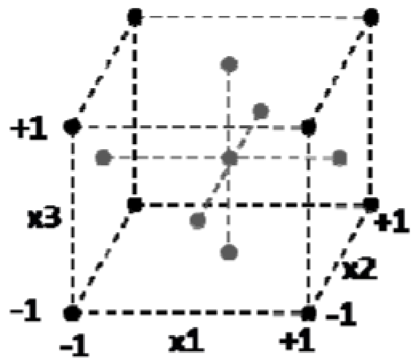

Figure 3. Face-centered central composite design (FCCD) [Ren et al., 2013].

30 design points are created in the design space of this study, which is made with three geometric parameters. Only the planform area is kept identical for all the design points, which are detailed in in Table 3. The geometries of the selected design cases in the design space are given in Figure 4.

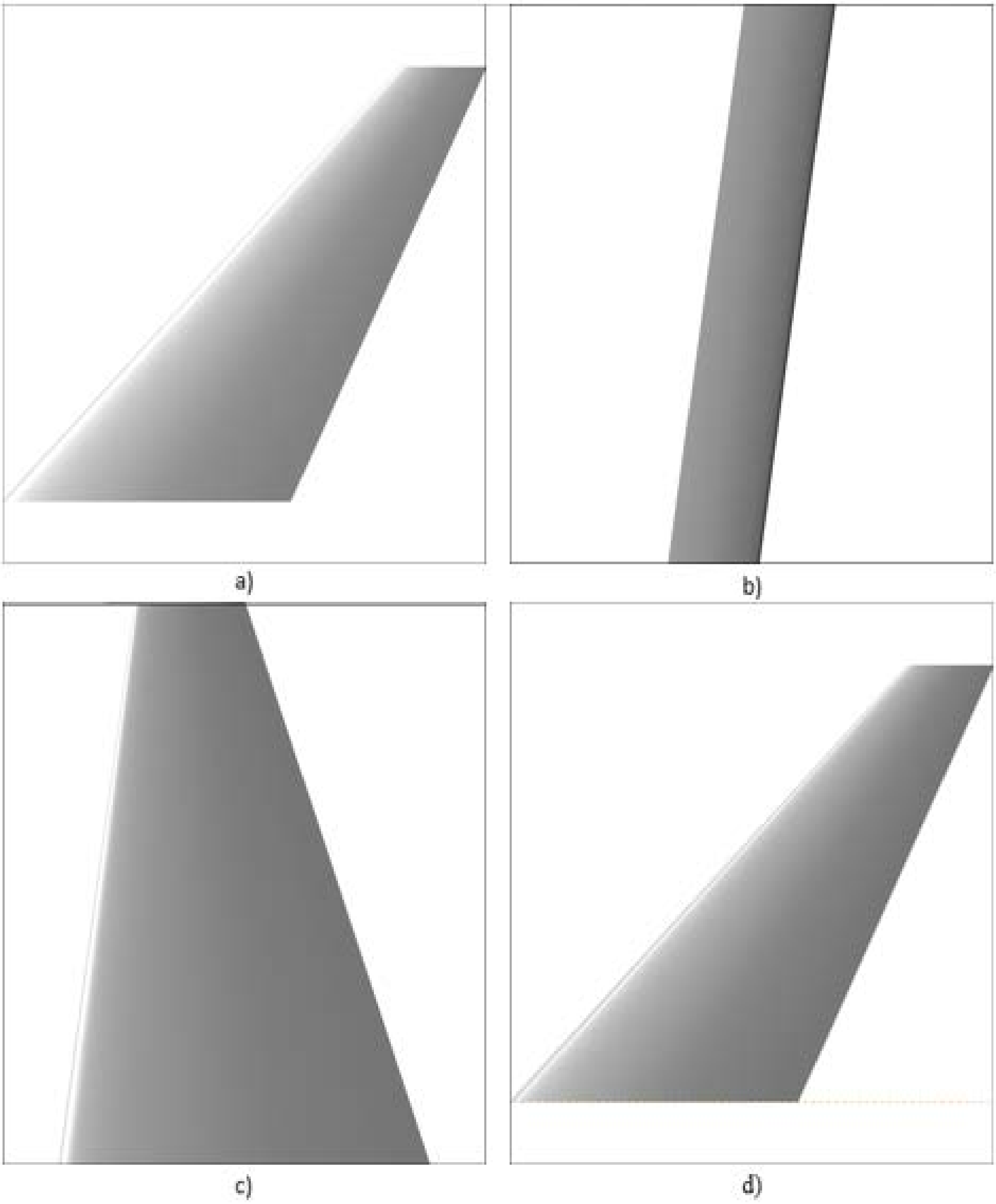

Figure 4*:* Design Space Geometry Examples, a) DP24, b) DP8, c) DP22, d) DP4

Table 3: Design Points Which Created Using FCC

DP	Sweep Angle	Taper Ratio	Area	Root Chord	Tip Chord	Span (m)	Aspect Ratio
0	26.7	0.56	0.75199418	0.805	0.451	1.1963	3.8
1	30	0.65	0.75199418	0.7	0.455	1.302154424	4.509625712
2	10	0.65	0.75199418	0.7	0.455	1.302154424	4.509625712
3	20	0.65	0.75199418	0.7	0.455	1.302154424	4.509625712
4	50	0.65	0.75199418	0.7	0.455	1.302154424	4.509625712
5	40	0.65	0.75199418	0.7	0.455	1.302154424	4.509625712
6	30	0.3	0.75199418	0.7	0.21	1.652734462	7.264766864
7	30	0.475	0.75199418	0.7	0.3325	1.456647322	5.643185751
8	30	1	0.75199418	0.7	0.7	1.0742774	3.069364
9	30	0.825	0.75199418	0.7	0.5775	1.177290301	3.686231863
10	30	0.65	0.75199418	0.4	0.26	2.278770242	13.81072874
11	30	0.65	0.75199418	0.55	0.3575	1.657287449	7.30484826
12	30	0.65	0.75199418	1	0.65	0.911508097	2.209716599
13	30	0.65	0.75199418	0.85	0.5525	1.072362467	3.058431279
14	10	0.3	0.75199418	0.4	0.12	2.892285308	22.24834852
15	20	0.475	0.75199418	0.55	0.26125	1.853914774	9.141028159
16	50	0.3	0.75199418	0.4	0.12	2.892285308	22.24834852
17	40	0.475	0.75199418	0.55	0.26125	1.853914774	9.141028159
18	10	1	0.75199418	0.4	0.4	1.87998545	9.39992725
19	20	0.825	0.75199418	0.55	0.45375	1.498369475	5.971086324
20	50	1	0.75199418	0.4	0.4	1.87998545	9.39992725
21	40	0.825	0.75199418	0.55	0.45375	1.498369475	5.971086324

22	10	0.3	0.75199418	1	0.3	1.156914123	3.559735763
23	20	0.475	0.75199418	0.85	0.40375	1.199591912	3.827212482
24	50	0.3	0.75199418	1	0.3	1.156914123	3.559735763
25	40	0.475	0.75199418	0.85	0.40375	1.199591912	3.827212482
26	10	1	0.75199418	1	1	0.75199418	1.50398836
27	20	0.825	0.75199418	0.85	0.70125	0.969533189	2.500005001
28	50	1	0.75199418	1	1	0.75199418	1.50398836
29	40	0.825	0.75199418	0.85	0.70125	0.969533189	2.500005001

APPLICATION

Mesh Independence

Before starting the optimization scheme solutions, a study of independence from the mesh was carried out. A 3D non-structured mesh was formed with prism cells in the boundary layers and quadrilateral cells in the remaining flow area. While doing this study, six different meshes were designed by decreasing the surface element sizes at each step. The flow condition for the independence from mesh study is Mach 0.84 (Reynolds Number: 11.72 million) angle of attack 3.06 degree. In this study Onera M6 Wing profile has been used and wing planform parameters' b, λ, c_r and Λ is in order 1.1963 meters, 0.562, 0.64607 meters, 30 degree [Schmitt and Charpin, 1979]. The features of mesh created are given in Table 4.

Table 4: Mesh Information

# of the Grid	**Mesh 0**	**Mesh 1**	**Mesh 2**	**Mesh 3**	**Mesh 4**	**Mesh 5**
Surface Sizing	0.095	0.075	0.0375	0.0125	0.00625	0.00312
Number of Surface Element	29511	37714	47800	61048	122598	355780
Number of Volume Element	1362852	1697200	2116879	2559106	4489650	1303179
Boundary Layer Sizing						
First Layer Thickness	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Number of Layer	25	25	25	25	25	25
Last Ratio	30	30	30	30	30	30
Mesh Quality						
Min. Ortogonal Quality	2.6125e-04	2.6275e-04	2.6253e-04	2.6253e-04	2.6253e-04	2.6298e-04
Max. Aspect Ratio	1.871e+05	1.017e+05	6.6586e+04	2.7819e+04	2.7819e+04	2.7569e+04

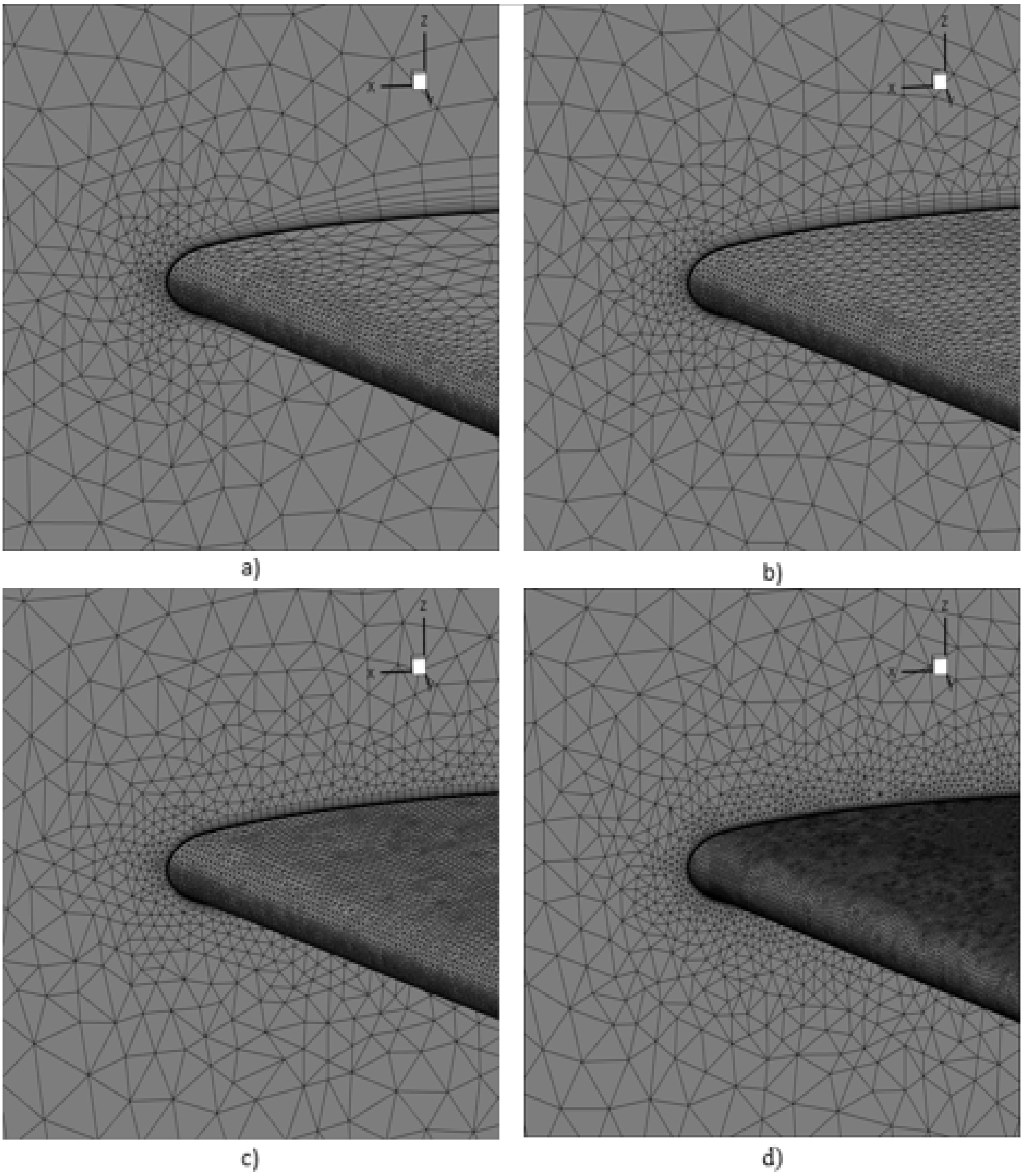

Figure 5: Wing Mesh Models, (a) Mesh 2, b) Mesh 3, c) Mesh 4 and d) Mesh5)

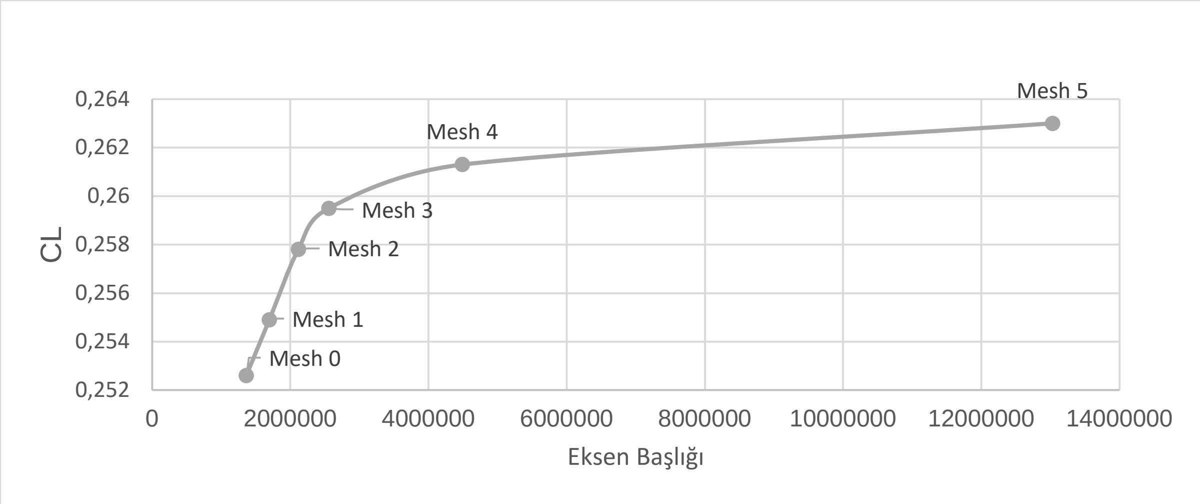

Figure 6: Coefficient of Lift for 5 Mesh

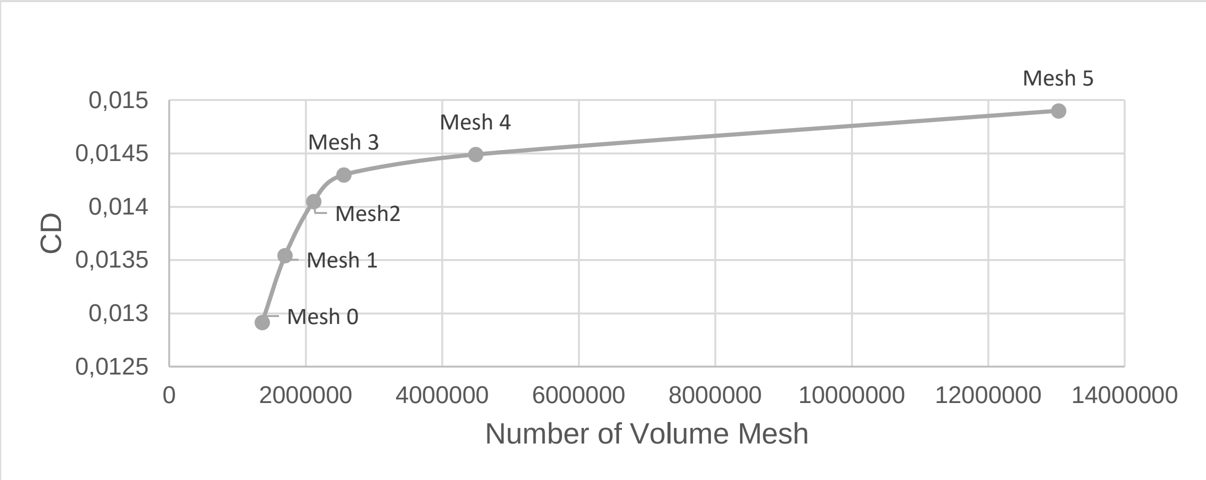

Figure 7: Coefficient of Drag for 5 Meshs

The variation of the coefficients of Lift (C_L), the coefficients of drag (C_D) resulting from mesh independence study is given in Figure 6 and 7. It was also derived from the results that the maximum error in aerodynamic coefficients between the 3rd and 5th meshes is around 1.5%. It was evaluated that Mesh 3, 4 and 5 results are accurate comparing to others. However for this study considering total computation time it is more feasible and suitable to use Mesh 3 since the study contains thirty design points, each has to be studied from 0 degree to the each Design Points critical angle of attack which contains up to 600 cases.

Response Surface and Optimized Wing Geometry

All Design Points have been solved by CFD and response surface have been fitted accordingly. Design restrictions has determined as minimizing coefficient of drag, maximizing coefficient of lift and fixing critical angle of attack at 10 degree. Response surface result have been compared with CFD results and also comparison with Onera M6 (DP0) has given in Table 6 and Figure 8.

Table 5: Comparison of Original and Optimized Geometries' Results (a) ONERA M6 (DP0) b) Optimized Geometry (DP30))

Design Point	**Original (DP0)**	**Optimized (DP30)**	**% Change**
Coefficient of Lift (C_L)	0.12942	0.13603	5.11
Coefficient of Drag (C_D)	0.00899	0.00866	-3.71
Critical Angle of Attack	10.5452	10.0362	Negligible

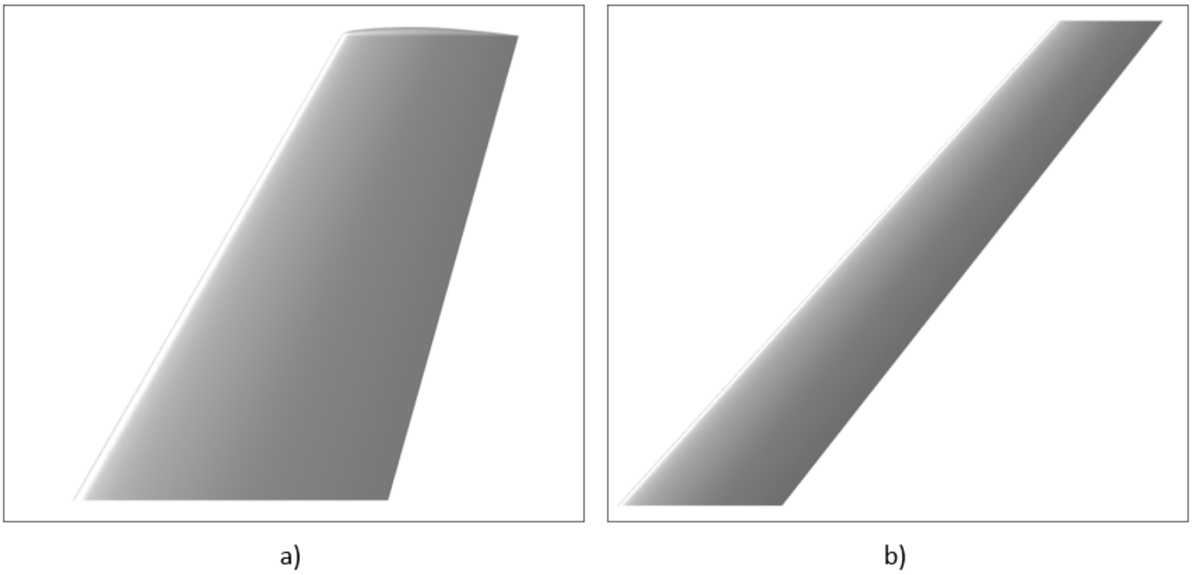

Figure 9*:* Comparison of Original and Optimized Geometries (a) ONERA M6 (DP0) b) Optimized Geometry (DP30))

CONCLUSION

In this study Onera M6 wing aerodynamic performance have been improved via parametric optimization method. Aerodynamic coefficients of Design Points have been obtained using CFD. In addition, the effects of the geometric parameters on the calculated aerodynamic coefficients were also revealed and the optimized geometry was achieved by using the response surface method.

The results obtained as a result of the study are listed below:

1. Optimum Sweep Angle is around 40 degree,
2. Coefficient of Lift has been increased 5.11%,
3. Coefficient of Drag has been reduced 3.71%,
4. Critical Angle of Attack has been kept above 10 degree which is closed to Onera M6

In this study Onera M6 planform optimization was taken into account however the wing profile could be studied in order to improve aerodynamic performance further in the future studies.

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