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FAST AERODYNAMIC ANALYSIS AND DESIGN OF A JET AIRCRAFT BY USING PANEL METHOD

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ABSTRACT

Fast and parametrical aerodynamic analyses for design of high speed jet aircraft is important especially during the initial design phases. In this study, different wing/body configurations defined with specific geometrical parameters for a jet aircraft are analyzed by using the panel method solver PANAIR. The analysis and design process is automated for the geometry and panel mesh generation and by using the Design of Experiment (DoE) methodology. The aerodynamic analysis and design study is performed for different flow conditions, i.e., ranges of Mach number and angle of attack, for given design requirements, starting from a representative fighter aircraft geometry similar to F-16. Various geometrical design parameters are selected and their effects on the aerodynamic performance are investigated through Response Surface Methodology.

INTRODUCTION

Fast aerodynamic analyses of complete aircraft geometry is important especially during the initial design phases. Usually during the design of a jet aircraft, it is required to investigate the effects of different geometrical parameters, such as airfoil, taper, twist, leading edge sweep, and wing weight, on the aerodynamic performance coefficients within a specified range of Mach numbers and required lift coefficients for different maneuvering flight conditions. With the advancements in computational power, Computational Fluid Dynamics (CFD) simulations have been performed for detailed aerodynamic and flow analyses in the literature and in the industry, however, they still have high computational cost. Therefore, fast aerodynamic analyses of complete aircraft based on panel methods are still important and being used during the initial design phases and in recent studies in the literature.

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In this study, different wing-body configurations defined with specific geometrical parameters for a jet aircraft are analyzed by using the panel method solver PANAIR. The analysis and design study is performed by using the PANAIR code together with the in-house utility codes PanINPUT and PanVISUAL [Adam et al, 2020], the CST code PanCST [Ugur et al, 2021], and the optimization code PanAUTO which is developed in this study [Kumser et al, 2021], and different Design of Experiment (DoE) methodologies.

The design study is done for a fighter aircraft geometry similar to F-16 by performing aerodynamic analyses for different flow conditions for a range of Mach numbers and angles of attack. The various design parameters, such as taper ratio, twist angle, leading edge sweep angle and airfoil, are selected and their effects on the aerodynamic performance are investigated through Response Surface Methodology.

METHODOLOGY

Aerodynamic Analysis

The aerodynamic analyses are performed for different wing/body configurations by using the panel method solver PANAIR. PANAIR is a higher order panel method software for subsonic and supersonic flows [Saaris, 1992]. This software uses linearized potential flow theory at subsonic and supersonic Mach numbers. It is preferable because the solution can be completed in a much shorter time than CFD software based on solving Navier-Stokes equations. By entering appropriate inputs to the program, any wing/body geometry can be analyzed and the results such as surface pressure coefficient and Mach distributions, and lift and drag coefficients for the geometry can be obtained. The PANAIR system is capable of solving boundary value problems with three-dimensional Prandtl-Glauert equation as given below: [Carmichael and Erickson, 1981].

$$\left(1-M_{\infty}^{2}\right)\frac{\partial^{2}\phi}{\partial x^{2}}+\frac{\partial^{2}\phi}{\partial y^{2}}+\frac{\partial^{2}\phi}{\partial z^{2}}=0 \tag{1}$$

Utility Codes:

Previously, several in-house utility codes have been developed to facilitate the analyses by PANAIR. These codes are pointwise2panair, panINPUT, panVISUAL [Adam et al, 2020], and panCST [Ugur et al, 2021]. The utility code, pointwise2panair, converts a GridGen mesh format from Pointwise, a grid generation software, into a suitable mesh format for PANAIR. The panINPUT is a utility code that creates an input file for PANAIR. This code allows the user to enter the required parameters easily interactively. The other utility code is panVISUAL which is able to read the mesh data from the output file of PANAIR and print the data in Tecplot format for visualization. Recently developed panCST code allows to create the aircraft geometry, i.e., wind and/or body, and to generate the panel mesh required by the panel method. This code is capable of creating various wing and body configurations by desired airfoil geometry by using the Class Shape Transformation (CST) [Kulfan, 2007] method.

In this study, the aerodynamic analyses of an aircraft model similar to F-16 aircraft geometry and an optimization study are performed by using PANAIR with these utility codes. A new utility code is also developed to achieve the optimization and analyses automatically. Although PANAIR and the utility codes are written in Fortran language, the newly developed utility code, PanAUTO, is written in Python language by using the available Python tools and modules to make automation of tasks easily and quickly. Moreover, the graphical user interface (GUI) tool-kits are also used to design an user-friendly interface, as shown in Figure 1 [Kumser et al, 2021].

Two optimization methods are decided to be used in PanAUTO. These methods are demonstrated in Figure 2. For both methods, panINPUT, PANAIR, and panVISUAL are used in the analysis. The main difference between these methods is the way of obtaining the geometry.

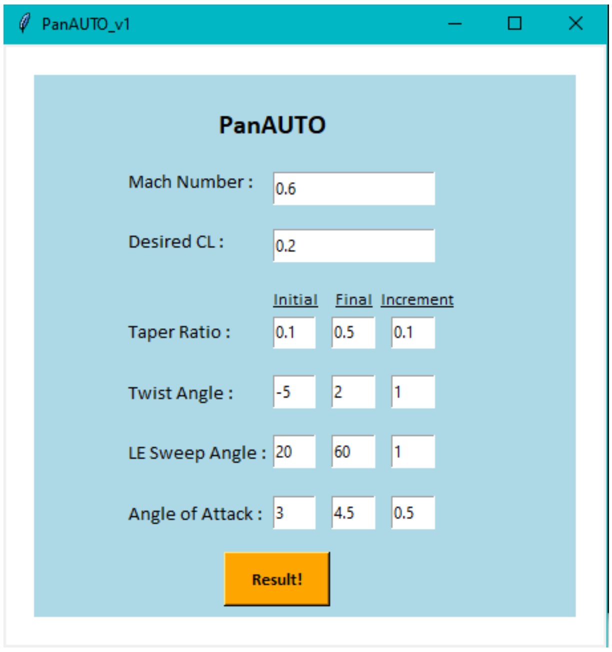

Figure 1: The interface of PanAUTO

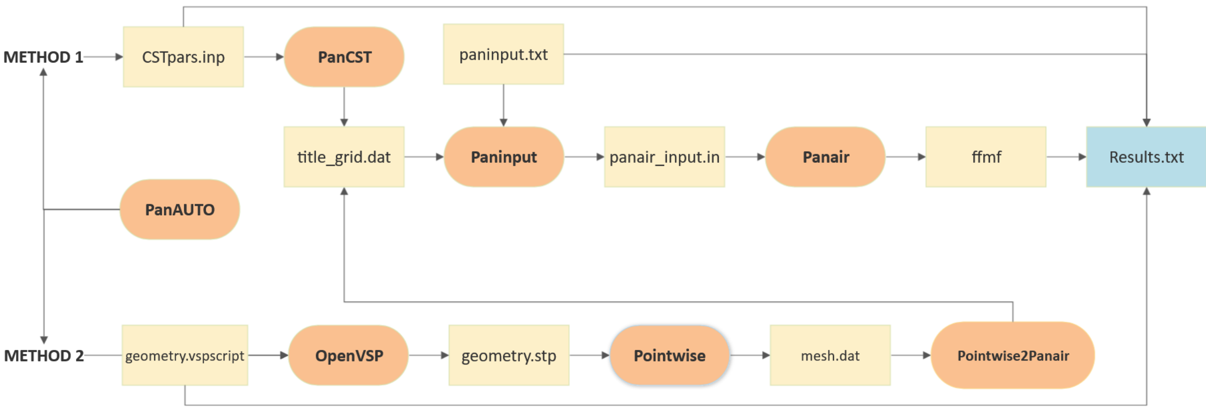

Figure 2: The flowchart of the applications showing the working order.

Geometry and Mesh Generation:

The geometry and mesh generation of a fighter jet aircraft is done by using two different approaches as shown in Figure 2. In the first method, panCST code [Ugur et al, 2021], which allows for automatically creating and meshing the geometry based on specific geometrical parameters, is used. In the second method, different geometries are designed with the help of OpenVSP, an open source program, then, the meshes are generated by Pointwise which is a commercial grid generation software.

In the first method, the airfoil geometry is obtained from the panCST. Since airfoil design is not to be changed throughout the optimization for this study, the airfoil geometry is selected once as NACA 64A204 airfoil which is the airfoil of F-16 wing. OpenVSP is used to obtain necessary CST parameters to create an airfoil geometry in panCST. In the Method 1, both the wing/body geometries and their panel mesh are created with the help of panCST and then the output file is transferred to other utility codes to complete aerodynamic analysis of the specific aircraft geometry. These steps are automatized by PanAUTO.

In the second method, OpenVSP and Pointwise software are used to create the geometry and mesh. The wing/body geometries are generated in OpenVSP by using vsp-scripts, and the panel mesh are generated in Pointwise by using Glyph scripts. After the geometry and mesh are created, the output files from these software are transferred to the related utility codes, and the analysis is completed.

In this study, both methods are used for comparison of results. However, the optimization process is completed by using the methodology explained in Method 1 that has simplified geometry and mesh generation by using the CST method.

Analyses are performed for the jet aircraft wing/body geometry created similar to F-16 aircraft. The fuselage and wing geometry of this fighter aircraft is designed with respect to the general data of F-16 [HAF Series Aircraft, 2003]. The detailed view is shown in Figure 3.

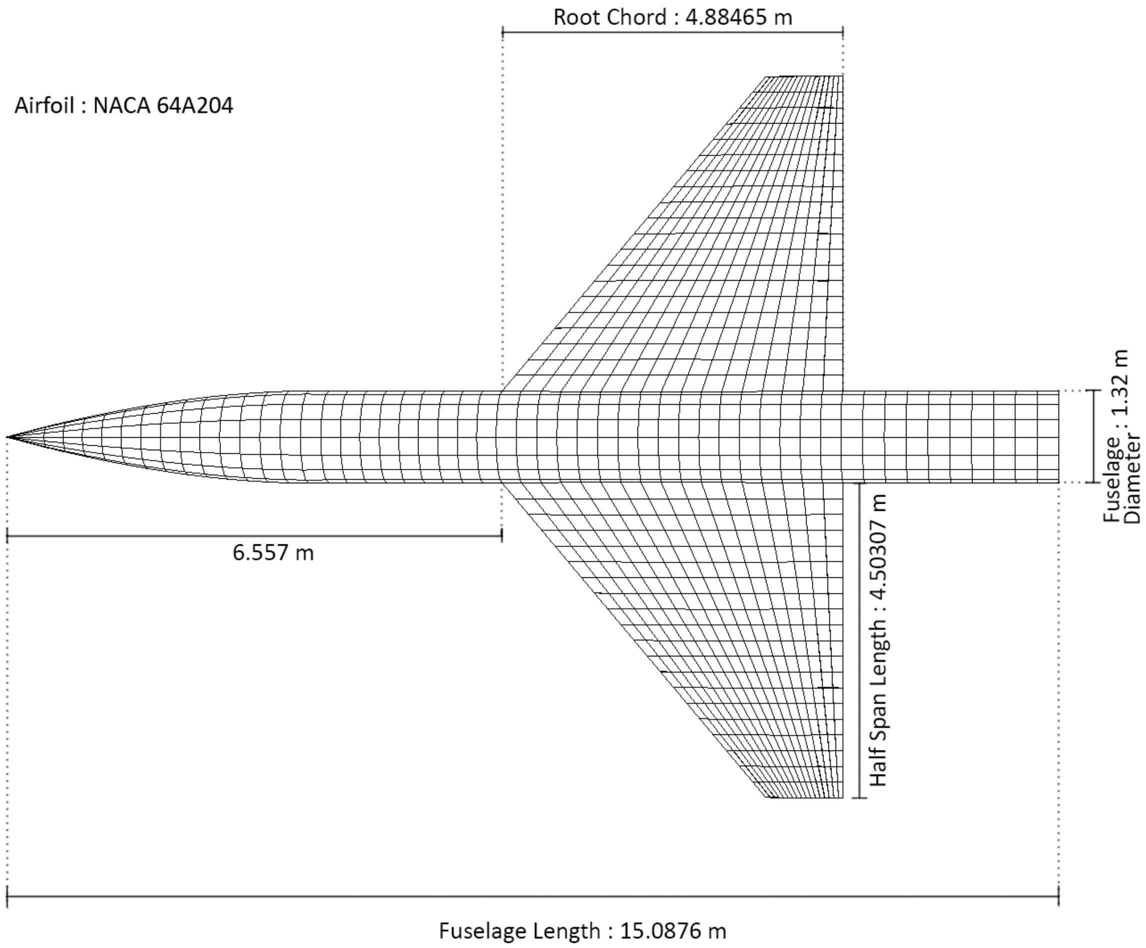

Figure 3: General geometric properties of F-16 aircraft

Wing Weight Estimation

Throughout the analyses, the weight of the wing is estimated by using an empirical relation which is demonstrated in Equation 2. This estimation is done by using the relation for U.S. Air Force (USAF) Fighter Aircraft [Carichner and Nicolai, 2010].

$$W_{wing} = 3.08 \left(\frac{K_{PIV} N W_{TO}}{t/c} \left\{ \left[\tan \Lambda_{LE} - \frac{2(1-\lambda)}{AR(1+\lambda)} \right]^2 + 1.0 \right\} \cdot 10^{-6} \right)^{0.593} \left[(1+\lambda) AR \right]^{0.89} S_w^{0.741} \quad (2)$$

where, K_{PIV} is wing variable-sweep structural factor (= 1.00 for fixed wings), t/c is maximum thickness ratio, W_{TO} is takeoff weight, in pounds (lb), Λ_{LE} is leading edge sweep, λ is taper ratio, AR is wing aspect ratio, S_w is wing area, in square feet (ft^2), and N is ultimate load factor ($=$ 13.5 for fighter aircraft).

Design and Optimization

During the design study, the aerodynamic analyses based on panel method are performed by using the procedure above and Design of Experiment (DoE) and Response Surface Methodology (RSM) are used to investigate the relations between the design variables and selected aerodynamics performance coefficients. The design space selection according to the design variables and the sampling and optimization procedures used in this study are described below.

Design of Experiments:

The main concern of the Design of Experiment (DoE) is to determine the design points (or test points/conditions) where the aerodynamic analyses are done and the responses (desired aerodynamic performance outputs) are obtained. To model and sample the design space, multiple methods are reviewed, and the Full Factorial Design and the Latin Hypercube Design methods are considered and compared in this design study.

Full Factorial Design:

Full Factorial Design method is a systematic design approach used for estimation of both major effects and interactions. This method is easy to use, however, a large number of test points are used depending on the number of levels or the number of factors [Natoli and Oimoen, 2019]. The number of test conditions is found by following relation:

$$(\#\text{of levels})^{(\#\text{of factors})} \tag{3}$$

where, the number of factors corresponds to the number of inputs. It is usually suitable for maximum of five variables as inputs, otherwise, it becomes computationally very expensive. The advantage of this approach is that it investigates all possible combinations in the design space [Das and Dewanjee, 2018].

Latin Hypercube Design:

Latin Hypercube Design is another method which places only one point on each level of every design variable [Viana, 2012]. Using this method, any number of test points to be analyzed can be specified unlike the full factorial design. Therefore, a significantly less number of points can be examined, which provides a less time-consuming approach. Another advantage of this method is that every variable is represented, therefore, even the ones with a minor effect on the response can be included.

Polynomial Regression:

To examine the nonlinear relation between the inputs (design variables, x) and a selected output (e.g., lift coefficient, y), a polynomial regression method is used. A second degree polynomial can be expressed as following:

$$y = \beta_0 + \sum_i \beta_i x_i + \sum_i \beta_{ii} x_i^2 + \sum_{i \le j} \beta_{ij} x_i x_j$$

As the degree of the polynomial increases, the accuracy of the prediction of the response by using the polynomial increases. However, the number of the coefficients and computational time also increase. Therefore, the degree is specified as 3 in the calculations.

The effect of every design variable on the output (lift coefficient) is found by using the PolynomialFeatures in the Scikit-learn library in Python tools and modules. Scikit-learn is an open source machine learning library that supports supervised and unsupervised learning. It also provides various tools for model fitting, data pre-processing, model selection and evaluation, and many other utilities [Pedregosa, 2011].

Response Surface Methodology:

Response Surface Methodology (RSM) can be defined as the techniques used in both mathematics and statistics to build an empirical model [Sarabia and Ortiz, 2009] for a given data set. A set of experiments are done in RSM to predict the response of the data obtained. An empirical model fitting to the data is obtained by applying the chosen design and being able to select the optimum conditions on the input variables which gives desired/extreme (e.g., min/max) responses in the range of interest [Khuri, 2017].

Design Variables & Objectives:

In this study, it is aimed to examine the effects of different geometrical planform parameters of jet aircraft on aerodynamic performance coefficients. The design objectives are selected as to minimize the drag coefficient and the absolute value of the moment coefficient while maintaining the flight condition which is set as Mach number of 0.6 (high speed case) and lift coefficient of 0.2. By taking the F-16 wing area as a constant parameter during the design, the different geometries are created and analyzed according to the given design space constraints as the design variables and their limits or range are shown in Table 1. The design space is created by changing the planform parameters in the specified range of the design variables. Then, the results are analyzed and discussed in terms of the design objectives.

Table 1: Design Variables

Design Variables	Lower/Upper Limit
Taper Ratio	0.1 / 0.5
Twist Angle	-5°/ 2°
Leading Edge Sweep Angle	20°/ 60°
Airfoil	NACA 64A204

RESULTS AND DISCUSSION

Validation Study for Aerodynamic Analysis

The aerodynamic analyses by using PANAIR are first performed for validation of the analysis procedure by using the F-16 aircraft model [Lan and Tseng, 1987] for which the experimental data [Nguyen et al, 1979] is available in the literature. The geometry similar to the experimental model is created by using both methods in PanAUTO: panCST which is Method 1 and Pointwise which is Method 2. The important parameters such as panel numbers, wing location, taper ratio, span, wing area, leading edge sweep angle, and a fuselage length of these wing/body configurations are kept the same for both methods. The created panCST and Pointwise geometries are shown in Figure 4 and 5.

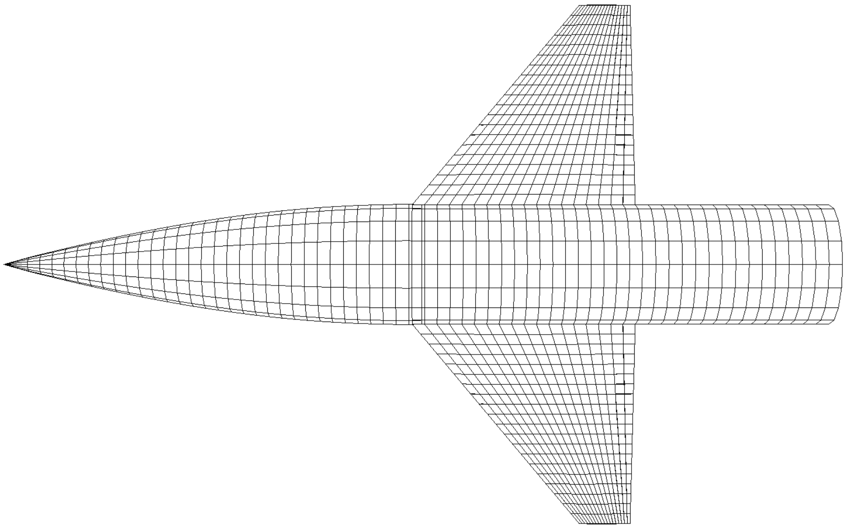

Figure 4: PanCST geometry (Method 1)

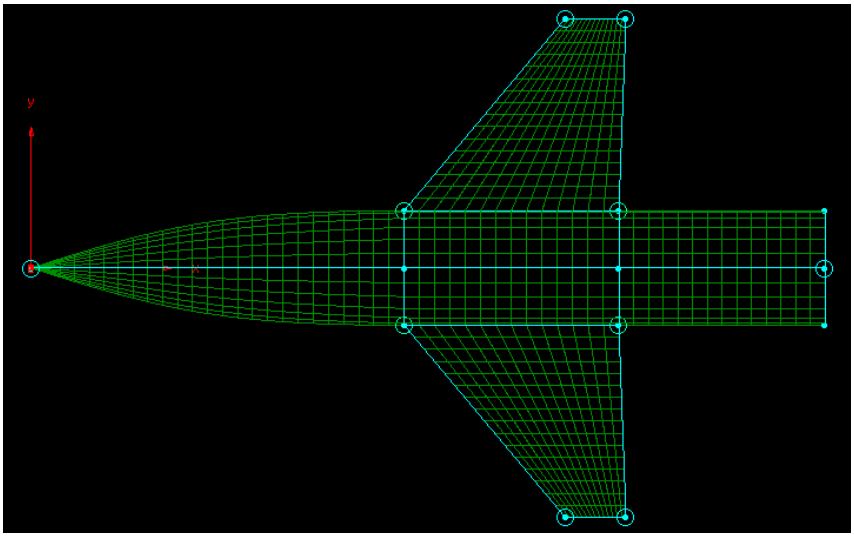

Figure 5: Pointwise geometry (Method 2)

Both wing only and wing/body analyses are performed from $0°$ angle of attack to $40°$ angle of attack for both panCST and Pointwise geometries to compare with the experimental data [Nguyen et al, 1979] as shown in Figure 6 and with a zoomed view for lower angles of attack (between 0° and 10°) in Figure 7.

The results for both wing geometries created by panCST and Pointwise overlap with each other. Generation of the circular fuselage body by using the fuselage diameter and generation of the mesh in these two different codes may differ a little, therefore, there is a slight difference between the results for the wing/body geometries. Consequently, these two methods gave similar results and the results are close to the experimental results especially at low angles of attack as the panel method being more accurate at low angles.

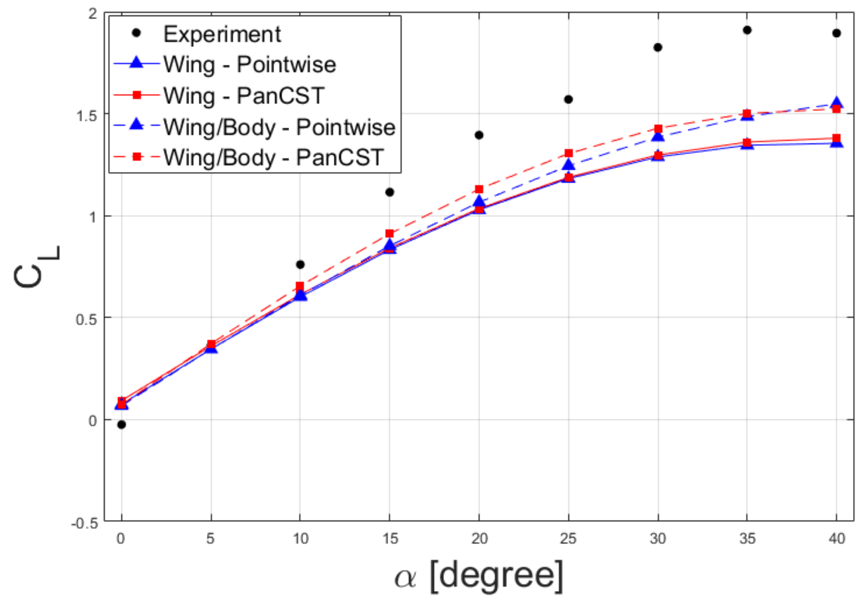

Figure 6: Comparison of lift coefficient between experiment data and Pointwise & panCST results

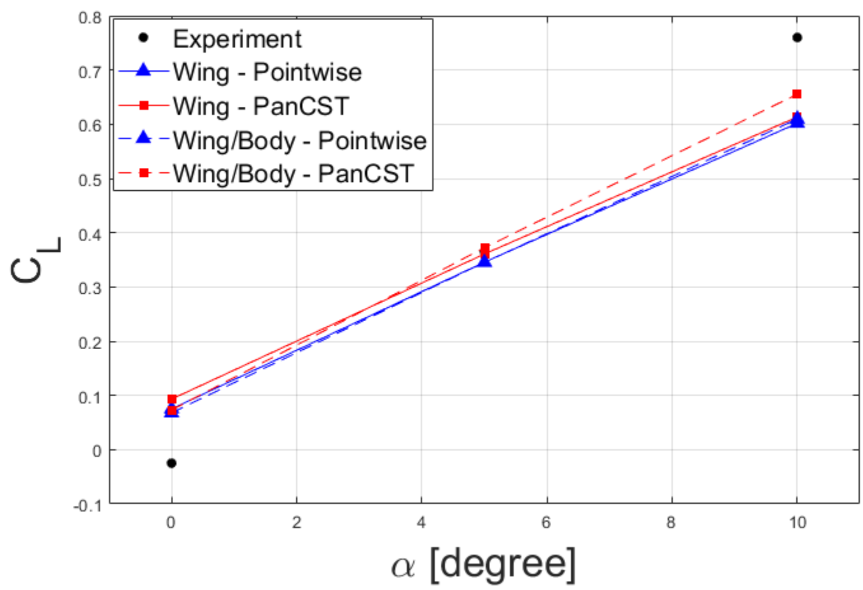

Figure 7: Comparison of lift coefficient between experiment data and Pointwise & panCST results for lower angles

Comparison of Polynomial Regression Predictions with PANAIR Results

After the aerodynamic analyses are completed, to use polynomial regression method to represent the input/output relations, a certain amount of the output data obtained from the PanAUTO code is excluded to be used as the test data. Rest of them are used to obtain the polynomial expressions by using Pyhton tools that give a table consisting of rows which show possible coefficients for the polynomials. After that, using those coefficients, polynomial expression can be obtained. The results obtained via polynomial regression and the output of the PANAIR analyses are compared as can be seen in Table 2 and 3. It is observed that the polynomial regression gives similar results with PANAIR, especially for the lift coefficient. On the other hand, the weight test results can be improved by using more data.

Table 2: Lift coefficient test

PANAIR Results	Polynomial Regression Results
0.1996	0.1996
0.1995	0.1995
0.2002	0.1937
0.2004	0.1999

Table 3: Weight test

PANAIR Results	Polynomial Regression Results
1225.38	1225.33
1257.87	1257.81
1321.27	1284.65
1348.73	1345.87

Design Study and DoE Results

In the design study, using the utility code called PanAUTO, an input file is prepared which includes the combinations of design variables resulting in the desirable lift coefficient. These combinations are obtained with the Full Factorial Design method to be able to check every possible test point. The effect of two design variables, taper ratio and sweep angle, on the lift coefficient can be seen in the following 3-D figure, Figure 8. Figure 8 can be obtained for any of two design variables versus the desired output aerodynamic performance parameter, e.g, lift coefficient. This type of figures gives a broader perspective in terms of the effect of design variables on the response.

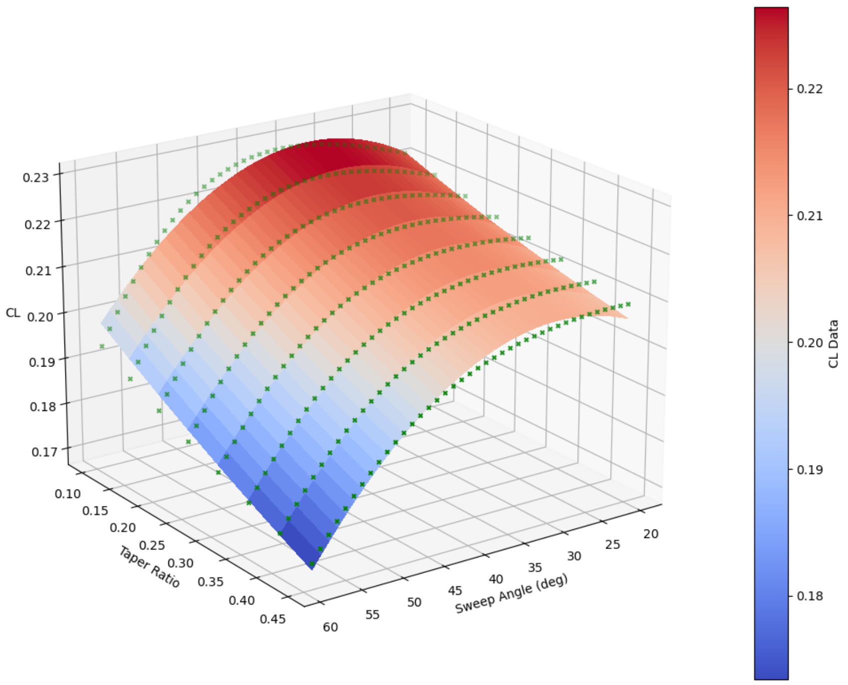

Figure 8: The effect of the taper ratio and sweep angle on lift coefficient

In the design study, considering the number of design variables, the Latin Hypercube Design method is also used as the most suitable choice considering the computational cost. In Table 4, the 19 combinations of parameters obtained by using 4 design variables in a specified limited range of the design space are shown in a matrix form. It is seen that the Latin Hypercube Design method suggests significantly less number of configurations compared to the Full Factorial Design method. Instead of checking every combination, it suggests to examine the randomly selected shown test points. The random distribution of two of the design variables in between the limits can be seen in Figure 9. Figure 9 shows the relation between two inputs, leading edge sweep and aspect ratio. Different such random distributions are obtained for any two inputs. However, to be able to compare the two design methods in terms of the number of configurations and accuracy of representation of the design space, the similarity of the results should be checked.

Table 4: Latin Hypercube Design Sampling: The Parameter Matrix for 4 Design Variables

Aspect Ratio	Taper Ratio	L.E. Sweep Angle	Twist Angle	Aspect Ratio	Taper Ratio	L.E. Sweep Angle	Twist Angle
4.07	0.22	42.00	-1.99	2.75	0.14	55.60	-4.51
2.63	0.32	22.80	-3.25	4.61	0.15	27.60	-4.09
2.57	0.11	58.80	-1.85	2.03	0.39	34.00	-4.65
4.67	0.48	54.00	-3.39	3.89	0.23	37.20	-0.17
4.37	0.20	43.60	-0.03	4.31	0.36	31.60	-4.79
2.69	0.13	46.80	1.93	3.95	0.26	20.40	0.81
4.55	0.45	48.40	0.11	2.39	0.29	26.80	-3.67
4.73	0.21	50.80	1.79	3.53	0.30	49.20	-2.97
2.45	0.37	50.00	-3.11	4.97	0.34	26.00	-1.57
2.27	0.47	30.80	0.95				

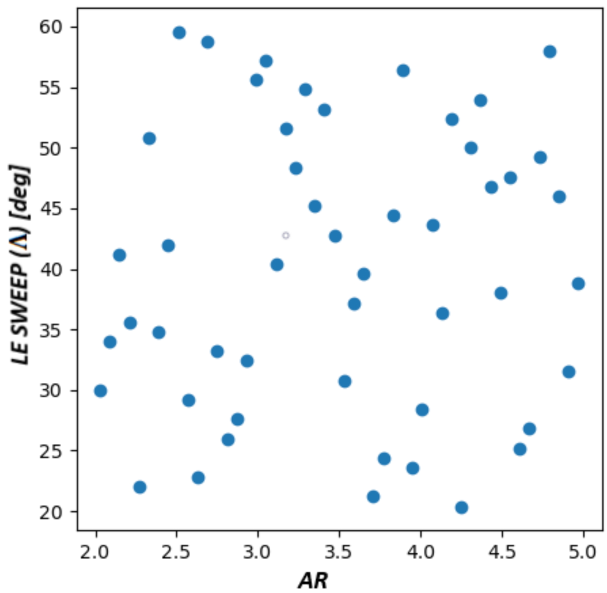

Figure 9: Leading Edge Sweep (Λ) vs Aspect Ratio

Results and Discussions for Design and Optimization

The design and optimization study of the selected jet aircraft model is done with the help of the developed code, PanAUTO runs together with PANAIR. Throughout this design process, the methodology in Method 1 is used and the aircraft geometry in Figure 3 is taken as a starting point. The Full Factorial Design method is used to create the design space for suitable fighter aircraft geometries in terms of design variables and objectives.

Total 8118 analyses are completed in 20 hours 43 minutes. This cost in terms of time depends on the computer performance and selected Design of Experiment (DoE) method. Among these analyses, 738 geometries are selected in accordance with the design objectives. The example results from these selected geometries are shown in Table 5 and also in Figure 10 with the lift coefficient as the specified design condition having a value of 0.2.

The analyses are made with varying planform parameters such as leading edge sweep angle, twist angle, and taper ratio. Additionally, the angle of attack values that satisfy the desired lift coefficient of 0.2, and target Mach number of 0.6 are found from the computational results for each geometry. As a result, the effects of planform parameters to different aerodynamic coefficients such as lift coefficient, lift coefficient slope, moment coefficient, moment coefficient slope, and induced drag coefficient are examined. The wing weight as a unit of a kilogram is also calculated for each geometry.

Table 5: Example Results from PanAUTO

Test	**Mach**	**Alpha**	**LE Sweep**	**Twist**	**Taper**	**Weight**	C_L	$C_{L\alpha}$	C_M	$C_{M\alpha}$	**Cdi**	**CL**$_{err}$ **(%)**
1	0.6	3.7185	20	-5	0.1	1241.771	0.20002	3.593	-0.30325	-5.0718	0.00373	0.01
2	0.6	3.7215	21	-5	0.1	1236.899	0.20002	3.5833	-0.30485	-5.0913	0.00369	0.01
3	0.6	3.7112	22	-5	0.1	1232.527	0.20002	3.5844	-0.30684	-5.1326	0.00367	0.01
4	0.6	3.7013	23	-5	0.1	1228.678	0.20002	3.585	-0.30885	-5.1744	0.00364	0.01
5	0.6	3.6921	24	-5	0.1	1225.378	0.20002	3.5856	-0.3109	-5.2156	0.00362	0.01
...	...	...	...	...	...	...	...	...	...	...	...	...
381	0.6	3.1361	31	-4	0.2	1335.221	0.20002	3.7053	-0.33248	-5.7462	0.00301	0.01
382	0.6	3.1358	32	-4	0.2	1341.461	0.20002	3.6973	-0.33489	-5.7834	0.00301	0.01
383	0.6	3.1367	33	-4	0.2	1348.733	0.20001	3.6881	-0.33735	-5.8201	0.003	0.005
384	0.6	3.1385	34	-4	0.2	1357.097	0.20001	3.6778	-0.33987	-5.8556	0.003	0.005
385	0.6	3.1414	35	-4	0.2	1366.617	0.20001	3.6664	-0.34245	-5.8911	0.003	0.005
...	...	...	...	...	...	...	...	...	...	...	...	...
718	0.6	3.0999	40	-4	0.3	1598.414	0.20002	3.6772	-0.36103	-6.224	0.00279	0.01
719	0.6	3.1149	41	-4	0.3	1621.332	0.20001	3.6549	-0.36401	-6.2504	0.0028	0.005
720	0.6	3.1316	42	-4	0.3	1646.167	0.20002	3.632	-0.3671	-6.275	0.00282	0.01
721	0.6	3.1516	43	-4	0.3	1673.044	0.20002	3.6056	-0.37024	-6.2957	0.00283	0.01
722	0.6	3.1706	44	-4	0.3	1702.101	0.20003	3.581	-0.37356	-6.3197	0.00285	0.015

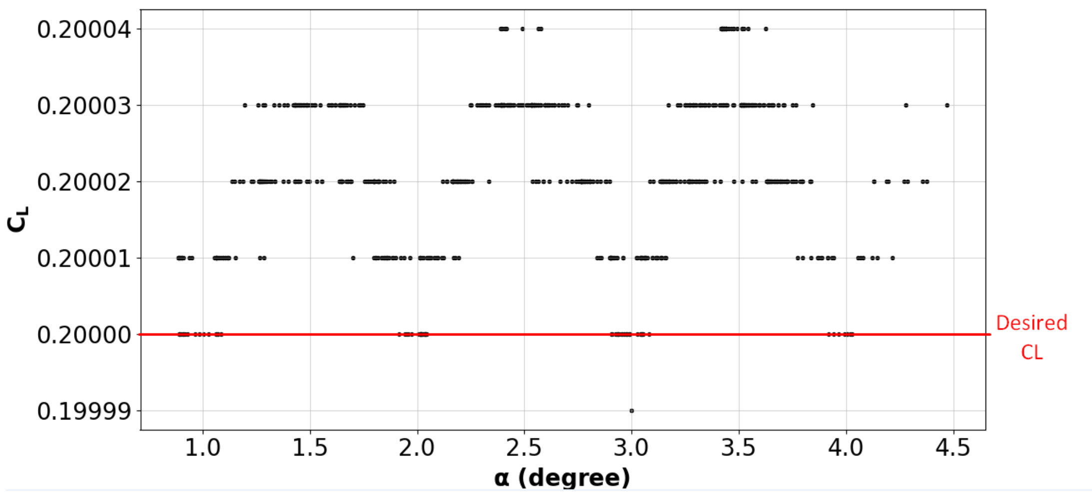

Figure 10: The deviation from the desired lift coefficient

The representative graphs of the computational results obtained from the design study are shown in Figure 10, 11, 12, and 13. In Figure 10, the deviation from the desired lift coefficient is shown for all geometries. As it can be seen from this figure, the errors are very minor, and lift coefficients are close to the desired one. In Figure 11, 12, and 13, the geometries with the minimum aerodynamic coefficients and the actual F-16 aircraft geometry are shown. From Figure 11, it can be observed that the geometry with minimum drag coefficient satisfies design objectives at around 3.1 degrees of angle of attack. This coefficient is considerably lower than the drag coefficient of actual F-16 geometry. Additionally, it can be seen from Figure 12 that the geometry with minimum absolute moment coefficient satisfies the design conditions at around 3.7 degrees of angle of attack. Moreover, the twist angle doesn't have any effect on empirical wing weight relation; therefore, its effect on the weight couldn't be observed in Figure 13.

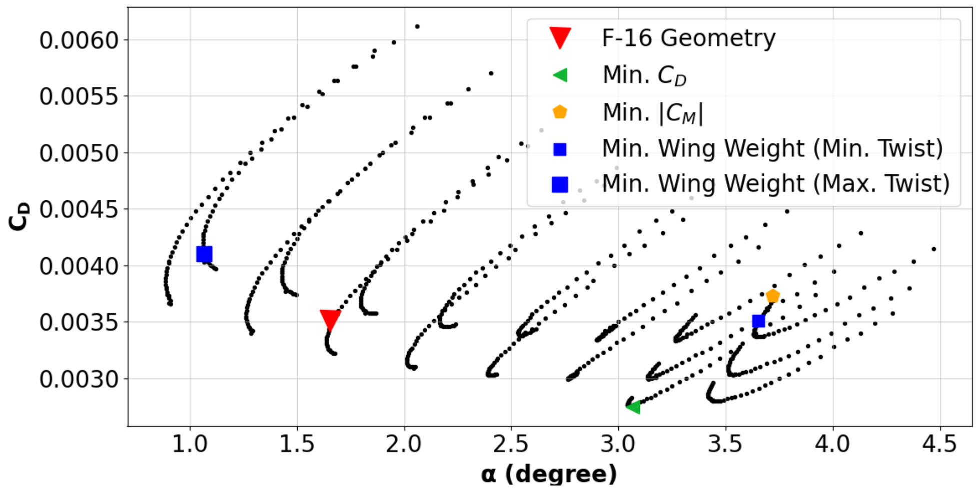

Figure 11: Drag coefficients and corresponding angles of attack for geometries

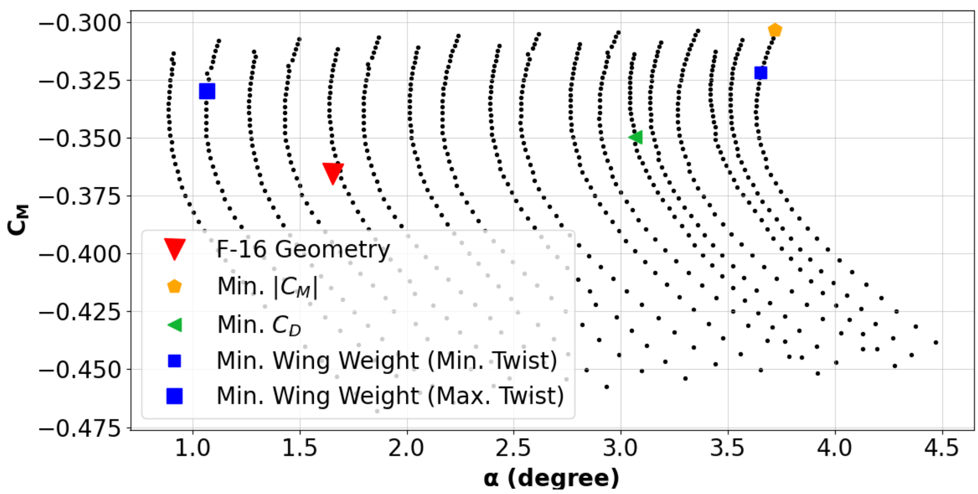

Figure 12: Moment coefficients and corresponding angles of attack for geometries

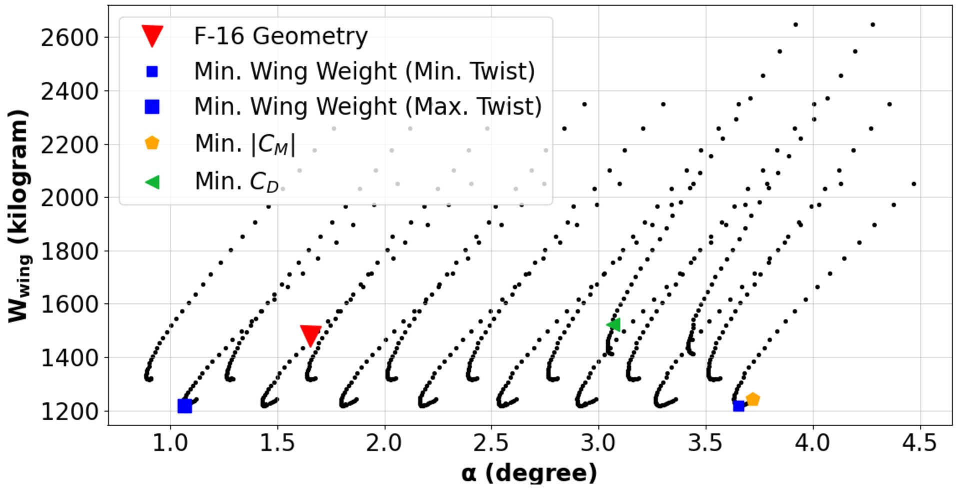

Figure 13: Wing weights of geometries

According to the most critical points in the above graphs, the aircraft geometries are visualized and shown in Figure 14, 15 and 16. It can be seen that the geometry with the minimum drag coefficient is very similar to the original F-16 geometry. When it is tried to minimize the absolute moment coefficient, it is observed that the taper ratio is lowered. Moreover, the lightest geometry is obtained by lowering the taper ratio. The apparent effect of the leading edge sweep angle on these parameters cannot be observed.

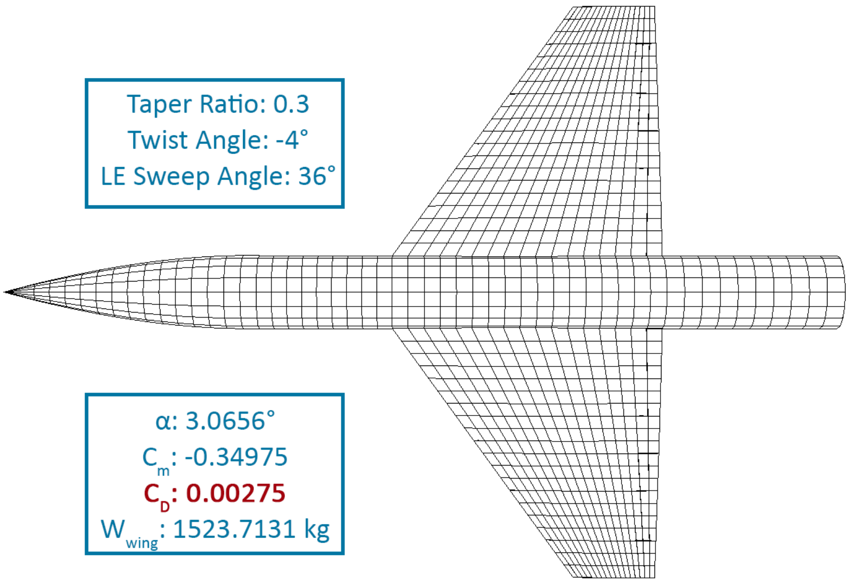

Figure 14: The aircraft geometry where the induced drag coefficient is minimum

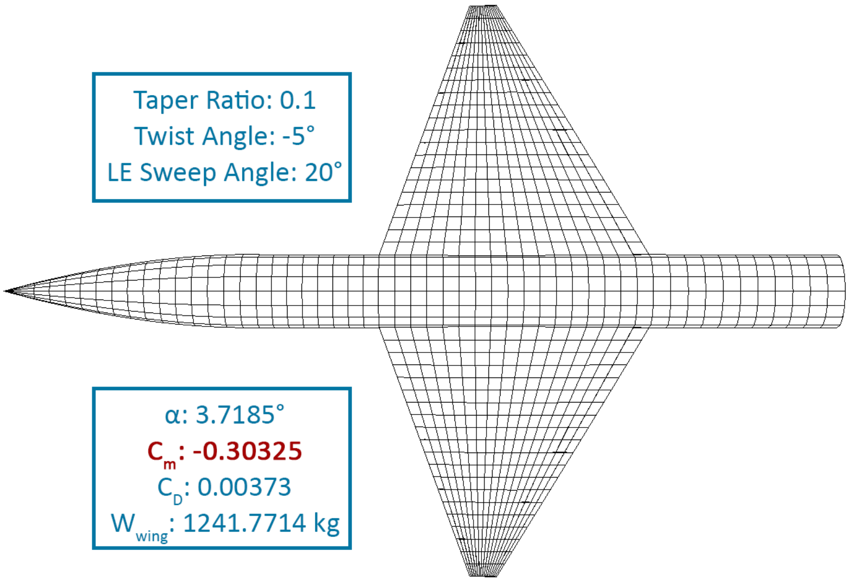

Figure 15: The aircraft geometry where the moment coefficient is minimum

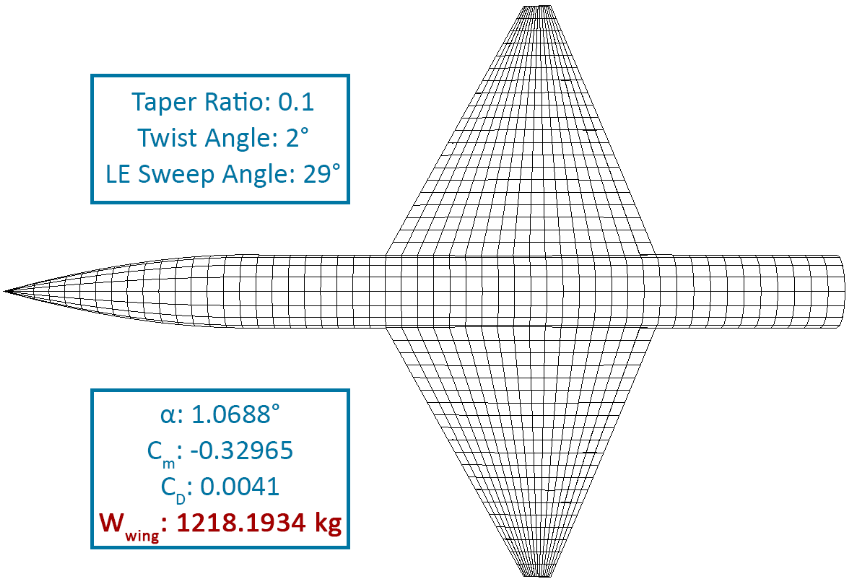

Figure 16: The aircraft geometry where the wing weight is minimum

CONCLUSION

In this study, an optimization study for the design of a fighter aircraft model with a simple wing/body configuration is done by performing aerodynamic analyses based on panel method by using PANAIR and newly developed PanAUTO codes. First, the reliability of the results from the analyses by PANAIR and PanAUTO is tested with the comparison of the available experimental data and the computational results obtained by two different approaches used in the generation of the geometry and mesh. In the design study, the design space is created by performing the fast aerodynamic analyses based on the higher order panel method according the specified flight condition and design variable constraints. Different design of experiment methodologies are discussed with an example of Latin Hypercube Design method providing less number of configurations in the design space to be tested thus resulting in less computational time. Polynomial regression method is also tested with the computational results providing a fast forecasting relations for the weight and the lift coefficient.

It gives less reliable results for the weight prediction which can be enhanced using more data. Finally, as an example, the sample geometries from the design space are created according to the specified design variable limits and compared in terms of minimum weight, drag coefficient and moment coefficient as the desired design objective parameters.

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