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GENERIC TRIM ANALYSIS AND SIMULATION ALGORITHM CREATION FOR DESIGN AND OPTIMIZATION OF THE FIXED WING AIRCRAFT

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ABSTRACT

In order to design a fixed wing aircraft, certain phases are needed to perform. From these phases, trim analysis and simulation are very crucial for design process. Trim and simulation analysis enable to calculate performance and stability characteristics of the aircraft. After aerodynamic, weight and engine database creation, the next step is trim analysis and simulations. However, database creation phase requires a huge amount of computing time, and for the preliminary design phase it is needed to perform quick analysis to optimize the geometry according to customer requirements. In this study a generic trim analysis and simulation algorithm will be studied without needing to create overall aerodynamic database.

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NOMENCLATURE

α	angle of attack
β	angle of sideslip
γ	flight path angle
$\delta_{aileron}$	angular deflections of ailerons
$\delta_{elevator}$	angular deflections of elevator
δ_{rudder}	angular deflections of rudder
X, Y, Z	components of the resultant force in the body-axis frame
L, M, N	components of the resultant moment in the body-axis frame
p, q, r	components of the aircraft angular velocity in the body-fixed reference frame
ϕ, θ, ψ	aircraft Euler angles
u, v, w	components of the aircraft velocity in the body-fixed reference frame
I	Inertia in the body-axis frame
V_{inf}	air velocity in the wind-axis frame
$\dot{()}$	time derivative
m	mass
AVL	Athena Vortex Lattice

INTRODUCTION

A design process requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation. These three operations must be integrated and applied iteratively and continuously throughout the lifecycle of the design [Sadraey, 2013]. After synthesis step is completed; aerodynamics, performance & stability, weight & balance and engine analyses should be studied. In general, a database is needed in order to start performance and stability analysis. However, it can be possible to complete trim phase without creating database, by using quick aerodynamic analysis method and Newton-Raphson algorithm [Millidere, Karaman, Uslu, Kasnakoglu, & Cimen, 2020]. To get the simulation results, nonlinear differential equations can be solved via integration methods like Runge-Kutta. By including trim and simulation analogy, the current study aims to develop a generic analysis algorithm which can be used for design and optimization processes of the aircraft design.

METHOD

Although optimization algorithms are regarded as the most important part of the design process, rapid and accurate analysis capabilities are quite crucial for an effective design. Having this capability provide to reach the optimum result by using a simple optimization algorithm in very short time interval. In traditional design algorithms, codes are created with time-consuming methods to calculate performance and stability parameters of the aircraft. However, in this analogy, many assumptions are used, and different equations are benefited from for each dynamic condition. This situation both decreases the accuracy and requires much more effort to set the formulations for all maneuvers separately.

Analytic equations for performance calculations needs to be fed with aerodynamic data to solve them properly. This process can be quite time consuming without any automatization. Moreover, stability, controllability and control surface sufficiency analyses are very hard to get from analytic performance calculations. Therefore, the independent performance calculation methods, which is used by traditional design codes, should be replaced with more accurate and practical methods. It is possible to gain capability to solve complex dynamic problems by boosting the accuracy without making concessions from rapidness. Figure 1 shows traditional and model-based design analysis analogies.

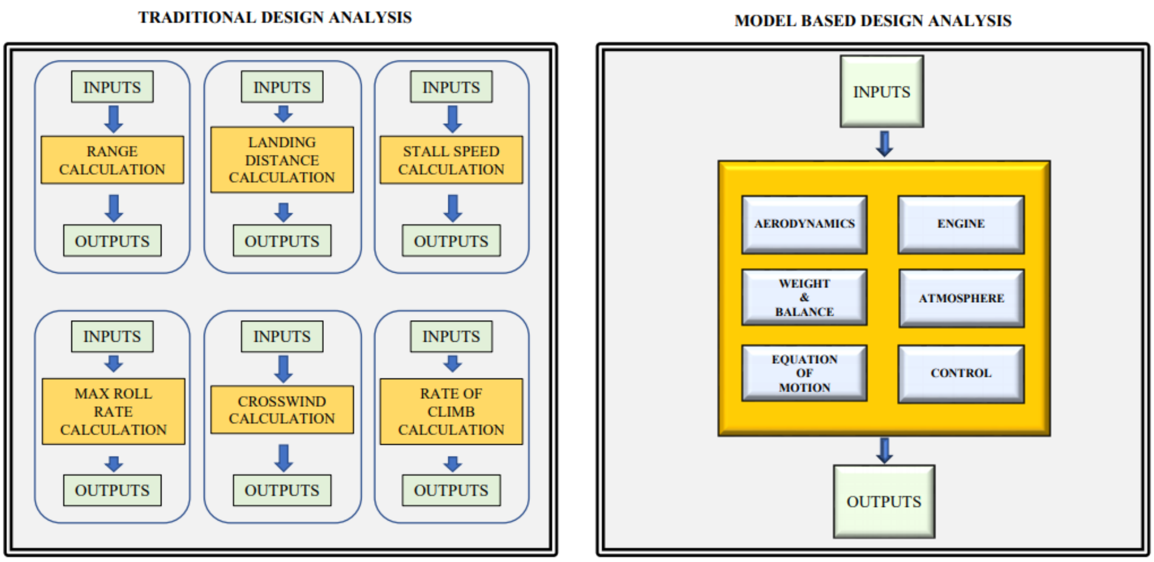

Figure 1: Traditional and Model-Based Design Analysis Analogies

Model Subparts

In the model-based design analogy, the needed disciplines are integrated to the model as blocks. These blocks feed the central equation of motion block concurrently.

<u>Aerodynamics Block</u>

Design process of an aircraft is very dependent to trim and simulation analysis. To get the results of these analysis, it is needed to have aerodynamic coefficients. In this situation there are e few aerodynamic analysis and calculation methods to apply on. Panel method, Vortex Lattice method, theoretical and empiric methods are some of these examples.

In the current study, a vortex lattice method (VLM) is decided to be used and among the existing VLMs, Athena Vortex Lattice Tool [Drela & Youngren, 2004] is selected to obtain the aerodynamic coefficients. In order to make automatize the algorithm, the aircraft geometry which is given as an input to AVL code is represented parametrically. The geometric inputs constitute the main part of the design parameters. Figure 2 shows all the AVL inputs and the corresponding outputs.

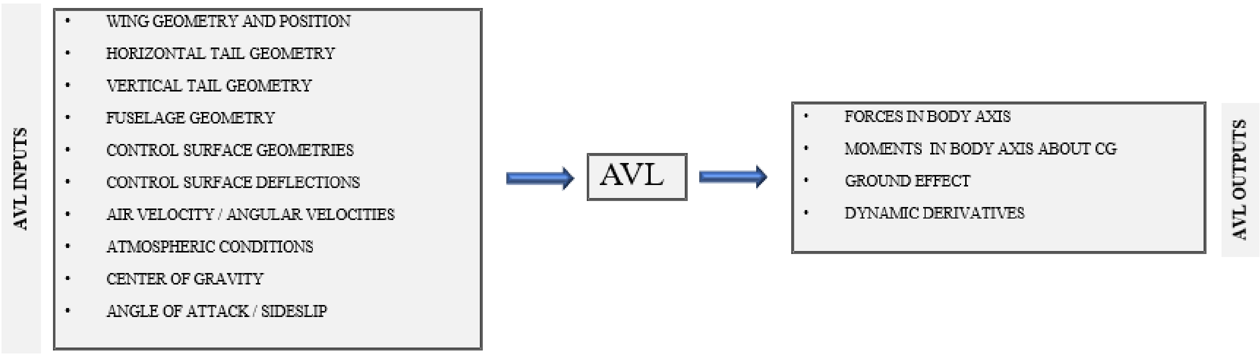

Figure 2: Input and Output Parameters of AVL Tool

AVL tool is capable to calculate the aerodynamic forces, moment coefficients and their derivatives with respect to all states. In addition, control surface definition and analysis are possible in this VLM tool. So, by using vortex lattice method, aerodynamic and stability characteristics can be obtained for various design alternatives.

Equation of Motion Block

The equation of motion block, which is the fundamental part of simulation, integrates the flight dynamics equations to the model. Equations from 1 to 6 show six degree of freedom equation of motion. According to this relations, trim point is calculated and initial condition of the simulation is determined. Although these six equations are very important and fundamental, they are not enough to get trim points for all flight conditions. The equations can be used for calculating trim point of straight flight condition.

$$X_A + X_T - mgsin\theta = m(\dot{u}^E + qw^E - rv^E)$$

Equation (1)

$$Y_A + Y_T - mgcos\theta sin\phi = m(\dot{v}^E + ru^E - pw^E)$$

Equation (2)

$$Z_A + Z_T - mgcos\theta cos\phi = m(\dot{w}^E + pv^E - qu^E)$$

Equation (3)

$$L_A + L_T = I_x\dot{p} - I_{yz}(q^2 - r^2) - I_{zx}(\dot{r} + pq) - I_{xy}(\dot{q} - rp) - (I_y - I_z)qr$$
Equation (4)

$$M_A + M_T = I_y\dot{q} - I_{zx}(r^2 - p) - I_{xy}(\dot{p} + qr) - I_{yz}(\dot{r} - pq) - (I_z - I_x)rp$$
Equation (5)

$$N_A + N_T = I_z\dot{r} - I_{xy}(p^2 - q^2) - I_{yz}(\dot{q} + rp) - I_{zx}(\dot{p} - qr) - (I_x - I_y)pq$$
Equation (6)

Some of the parameters which are used in Equations (1)-(6) are derived values where X_A, Y_A, Z_A, L_A, M_A, N_A parameters are aerodynamic forces and moments. They can be obtained only by performing aerodynamic analysis. While doing these aerodynamic analyses, coupled effects can be ignored for the sake of simplicity.

Also, X_T, Y_T, Z_T, L_T, M_T, N_T parameters represent the engine forces and the moments. It depends on altitude and temperature parameters. It should be formulated or created with a database to see effects of the parameters over the engine power and thrust.

These six equations also include inertia data of the aircraft. For the different amount of fuel, aircraft has different weight, center of gravity and inertia. Thus, throughout the flight, these parameters can change from takeoff to landing. As a result, all these parameters should be calculated and implemented to the equation of motion.

In order to obtain trim point and simulation result, kinematic equations should be included also. Euler angles and position equations enable to perform full simulation for a trimmed aircraft (Eqs.7-9).

$$\dot{\phi} = p + q(sin\phi + rcos\phi)tan\theta$$
Equation (7)

$$\dot{\theta} = qcos\phi - rsin\phi$$
Equation (8)

$$\dot{\psi} = (qsin\phi + rcos\phi)sec\theta$$
Equation (9)

For a trim analysis, all derivative terms inside of the six equations of motion should be equal to zero, which means that the angular and linear velocities do not change with time. However, these conditions do not surely reveal that the trim point is steady. If a trim point is steady, then the elevation and the bank angle derivatives should also be zero.

At the straight flight, the angular velocities are equal to zero. Thus, derivatives of Euler angles will be zero. In this case, it can be said that the trim of the straight flight is steady. It enables states to keep constant throughout the whole flight simulation by assuming the air density as constant and there is no external disturbance or gust.

If derivatives of the angular and linear velocities are zero but derivatives of Euler angles are not zero, then the trim point is not steady. After a while, states will differ from the trimmed values because of the nonzero Euler angle derivatives.

Additional Blocks

Besides aerodynamics and equation of motion blocks, other additional blocks are required to get a complete model of the aircraft. For the engine analysis, thrust value is calculated which belongs to the various types of engines for different atmospheric conditions. At the weight and balance sections, the weight related values are automatically calculated by using empiric, theoretical and statistical methods. In the landing gear section, all dynamic effects of the landing gear are included. Therefore, for the take-off and landing analysis, no major assumptions are required. In addition, the effects of atmospheric conditions for different altitudes and temperatures are included in the simulation.

Additionally, in control block, the system is linearized, and the characteristics of the aircraft detected. For the autopilot algorithm, the inverse simulation method is used. The method can detect required control surface deflections for defined maneuvers. Therefore, the control capability of different design alternatives can be simulated. After getting trim points by using six degrees of freedom model, the implementation of the control algorithm is performed. Linearizing system and detecting characteristics of the aircraft will be possible with the help of this methodology.

By use of this additional disciplines, trim and simulation analysis can be completed by considering all effects. Blocks are created by considering multidisciplinary point of view. Therefore, any block can be replaced with up-to-date methods or algorithms.

Trim And Simulation Algorithm

In order to prove that all the design aims are satisfied, the performance and stability analysis should be checked. For a unique aircraft design, the main method to obtain performance and stability responses are the trim and simulation analysis. By using quick aerodynamic analysis, performance and stability analyses can be got simultaneously via trim and simulations. Therefore, the optimization algorithm can detect a series of design parameters which give the best combination for the desired performance.

Parameters of equations of motion which is used for the straight flight trim and corresponds to the cruise, climb and descend conditions are tabulated in Table 1.

Table 1: Straight Flight Trim Algorithm Parameters

Inputs	**Velocity, Altitude, Throttle, Weight**
Zero terms	P, Q, R, ϕ
Unknown terms	$\alpha, \beta, \theta, \delta_{elevator}, \delta_{aileron}, \delta_{rudder}$
Constrained terms	$\dot{V}_{inf}, \dot{\alpha}, \dot{\beta}, \dot{P}, \dot{Q}, \dot{R}$

Table 2: Numeric Calculation Methods

	Numeric Calculation Method
Trim Optimization	Newton Raphson Method
Simulation Integration	Second Order Runge Kutta Method

The methods which are used in the model-based analysis are tabulated in Table 2. Because of the high accuracy level, less computing time and easy applicability advantages, Newton Raphson Method is found to be more suitable for trim calculations compared to the other numeric methods [J.C., 2014]. In addition, for integration, second order Runge-Kutta Method is used.

RESULTS

In this study, an algorithm is developed, which can provide the database needed by six degree of freedom model in a very short time interval. In addition, the required control surface deflection angles can be obtained for any desired maneuver. The algorithm is based on the analysis of the specific aerodynamic conditions which are required for the related flight conditions instead of the overall database. So, it can be detected trim point, run simulation, and set controller algorithms for a random geometry without any need for the pre-calculation or pre-analyses. In this situation, any maneuver can be instantaneously simulated by defining flight condition. Table 3 shows different flight conditions and maneuvers to validate model-based design analogy. The variety of maneuvers which started from different velocity, altitude, flight path angle, flap deflection and load factor are simulated. Descending turn, pull up, landing and climb analyses are completed for two different geometry which is defined in Table 4.

Table 3: Flight Conditions for Validation Study

Flight Conditions	Descending Turn	Pull Up	Landing	Climb	Inverse Simulation Controller
Velocity (m/s)	60	60	25	35	35
Altitude (m)	400	1000	1	15	1000
Load Factor (g)	4	4.5	NA	NA	NA
Gamma (deg)	-10	-15	-1	NA	0
Flap Deflection (deg)	0	0	20	0	0
Throttle Level	NA	NA	NA	100%	NA

After the creation of the dynamic model, two different geometic alternatives are determined to compare with each other in Table 4. Taper ratio, aspect ratio, incidence angle, dihedral angle and elevator chord ratio are determined as the geometric design variables. Also friction coefficient between runway and landing gear wheel is changed in alternative geometry. To see all effects of these geometric and environmental varieties, a number of simulation and trim analyses are conducted.

Table 4: Parameters for Two Different Geometries

Geometric Parameters	**Base Geometry**	**Alternative Geometry**
Taper ratio	0.55	1
Aspect ratio	7	5
Incidence degree	2	5
Dihedral degree	5	15
Elevator chord ratio	25%	40%
Runway Friction Coefficient	0.75	0.56

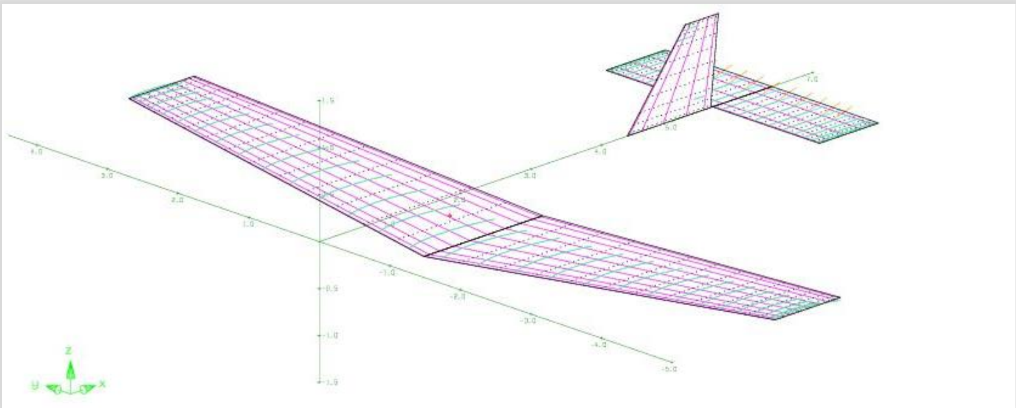

Figure 3: Base Aircraft Geometry (Isometric View)

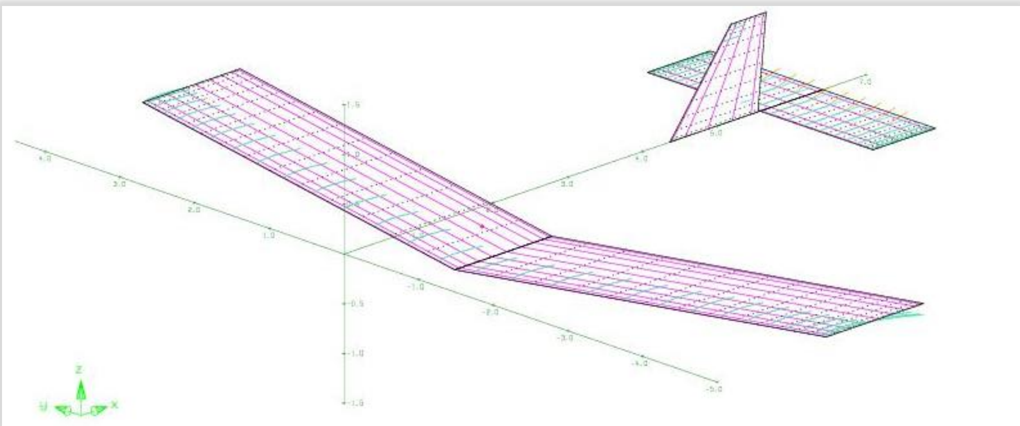

Figure 4: Alternative Aircraft Geometry (Isometric View)

Figures 3 and 4 show base geometry and the alternative geometry, respectively. For these two-geometries, the trim and the simulation results are obtained by use of the algorithm developed.

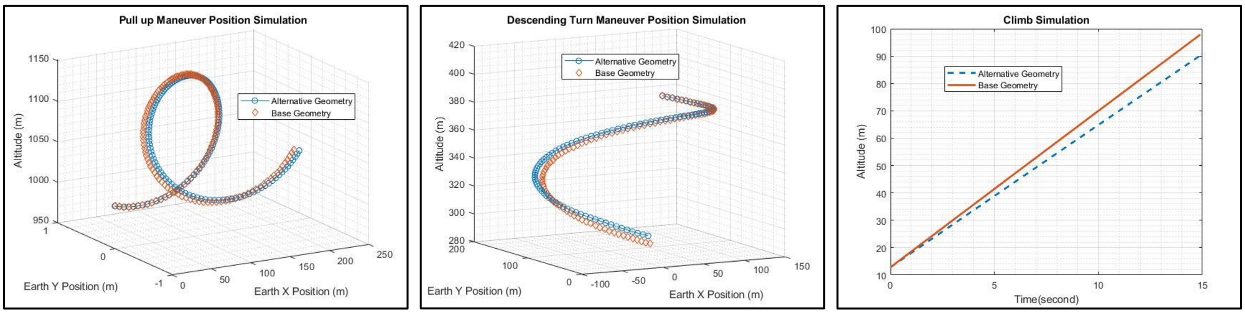

Figure 5: Pull Up, Descending Turn, Climb Simulation Results

In Figure 5; the results of the pull up, descending turn and climb simulations can be observed, which start from the same flight conditions, for the two different geometries investigated. In figure, it can be seen that flight path is slightly different for different geometric inputs. For example climb simulation shows the climb performance is better in base geometry when compared to alternative one.

Moreover, Landing simulation results can be seen from Figure 6. After touchdown point, the time and distance, which are needed to stop the aircraft, can be obtained. In addition, Table 5 shows the numerical values of these results. In landing simulation results, effects of both geometric and environmental design parameters can be observed.

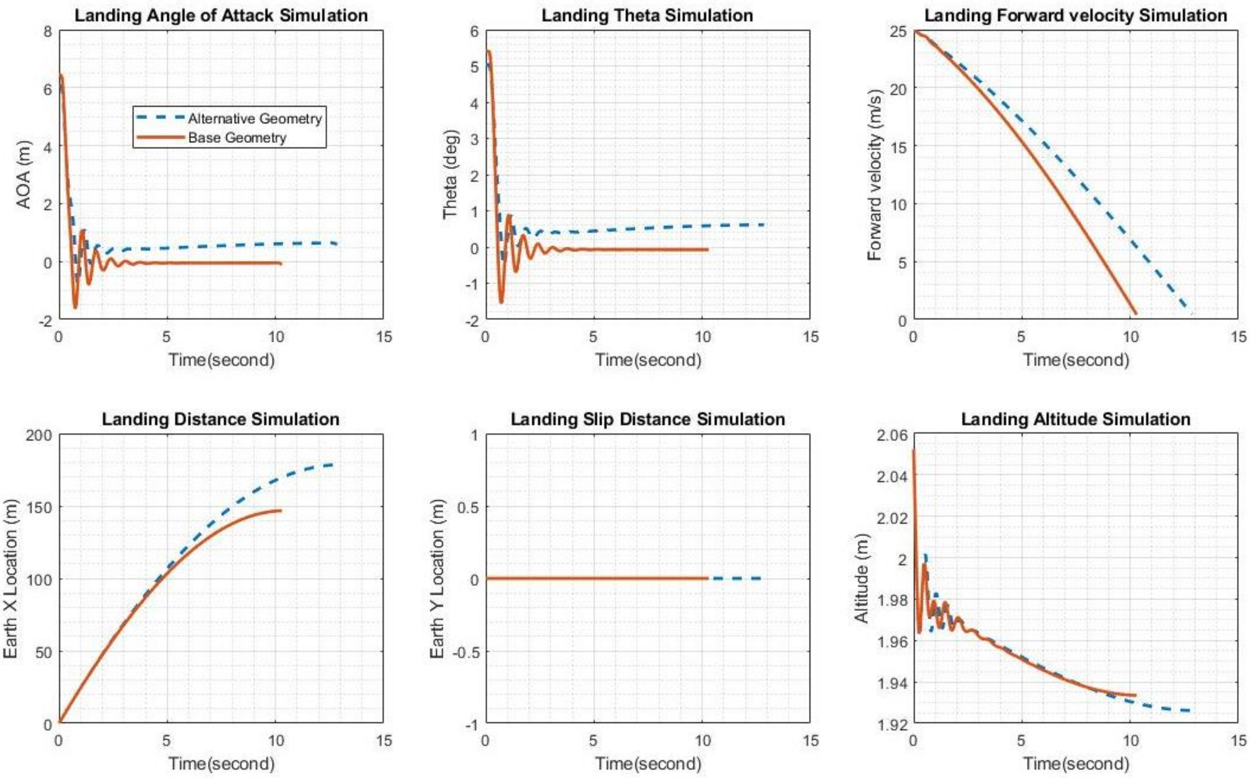

Figure 6: Landing Simulation Analysis Results

Table 5: Landing Time and Landing Distance for Both Geometries

	Landing Time (sec)	**Landing Distance (m)**
Base Geometry	10.3	148
Alternative Geometry	12.9	179

From Figure 6 and Table 5, it can be observed that base geometry has smaller landing distance and time with respect to the alternative geometry. Landing distance is 31 meters shorter and landing time is 2.6 seconds shorter than alternative geometry. This shows that base geometry gives better performance, because decreasing landing time and distance, provide pilot to stop the aircraft easily.

Additionally, control surfaces are used to control the aircraft. By the help of elevator and aileron, desired AOA and AOS path are tracked. In the Figure 7, amount of deviation of validated path from desired path can be observed as quite acceptable. Moreover, Figure 8 shows elevator and aileron deflection which is required to get desired AOA and AOS values. These implementations are completed with help of model-based design analogy.

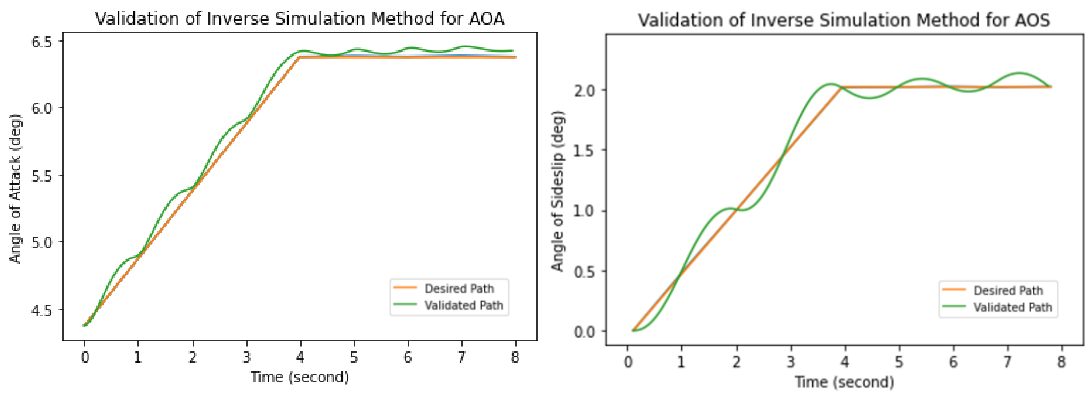

Figure 7: Inverse Simulation Controller for Desired AOA and AOS Path

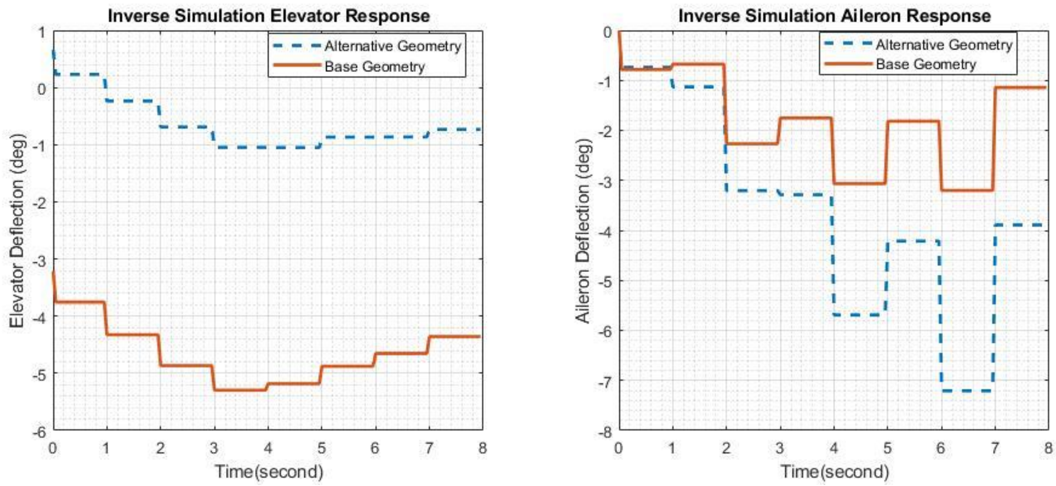

Figure 8: Inverse Simulation Controller Control Surface Responses

By using controller algorithms besides trim and simulation analysis, it can be possible to set a connection between input and output parameters of the design process. After this step, it is aimed to get the optimum design input parameters which give desired output combinations by using various optimization algorithms.

CONCLUSION

For an aircraft analysis and the design phases, the trim and the simulations are very crucial. Without performing a trim analysis, realistic results cannot be obtained. This means design of the aircraft cannot be converged to resultant geometry without trim calculations. In this study, as a trim solver, Newton Raphson is used. For the simulation phase, the second order Runge Kutta method is determined as the best choice for the numerical solver. These methods enable analysis to give realistic and accurate results. In addition to the trim and simulation methods, some side methods, like trim maps, helps to solve the equation of motion correctly. With the help of the simulations and the eigenvalue detection, the stability characteristics of the airplane can be predicted for any altitude, velocity, and weight combinations. In addition, by use of the generic trim and simulation analysis algorithm, the performance and the stability characteristics of the aircraft can be observed without any initial database preparation or computation. However, it is needed to define geometric parameters as accurate as possible before starting analysis. It will help the designer to optimize the design of the aircraft accurately in very short time.

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