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INVESTIGATION OF WAVEOFF MANEUVER CAPABILITIES OF JET AIRCRAFT WITH TRIM-BASED MANEUVER METHOD

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ABSTRACT

This paper studies quasi-steady trim-based maneuver method for checking the aircraft capabilities while performing waveoff maneuver with 6-DOF aircraft model and compare the results with the piloted simulation test results. The aircraft performance adequacy at waveoff maneuver is investigated.

Keyword: Waveoff Maneuver, Aircraft Performance Simulations, Quasi-steady Trim-based Maneuver Method

INTRODUCTION

Naval aviation is one of the most challenging area for airplane operations. Suitability of an aircraft to navy operations must be investigated precisely. Recently, carrier suitability of land-based aircraft were investigated [Hernando and Martinez-Val, 2012]. In these operations, waveoff maneuver capability is one of the crucial performance parameters for aircraft landing safety. Therefore, accuracy of waveoff capability analyses are significant while investigating the aircraft compatibility to navy operations. Waveoff is defined as an aborted landing attempt during which the air vehicle does not touchdown [MIL-STD-3013, 2003]. Unlike the other steady flight phases like climb, descent or cruise, waveoff is a quite dynamic maneuver. Accordingly, pilot inputs must be considered while performing maneuver capability. Moreover, engine thrust transition and control surfaces actuator dynamics are important to ensure aircraft maneuver capability. Therefore, all the factors should be added to analysis to increase accuracy. It is not easy to perform such analyses without using flight control systems. Quasi-steady trim-based maneuver method provides the pilot input only with the six degrees of freedom (6-DOF) aircraft model without applying any flight control systems or simulation tests as mentioned later in this paper. Validation of trim-based waveoff analyses with piloted simulation tests are also important to show reliability of method. Therefore, 6-DOF aircraft models are built for flight mechanics and aircraft performance analyses to determine the characteristics of the designed aircraft. By using the 6-DOF model of the aircraft, performing the maneuver is optimized and the more accurate performance results are obtained by simulating the aircraft in different flight conditions. To conclude, the more accurate the 6-DOF

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model results in the more realistic performance analyses. Trim-based maneuver method is used to calculate landing performance and validated in previous study [Dursun and Erturk, 2021].

The paper is organized as follows. Section II explains the waveoff maneuver. Section III describes the simulation environment for the 6-DOF nonlinear aircraft model. Section IV details the trim-based maneuver method with the 6-DOF plant model. The results of the trim-based maneuver methods for waveoff performance parameters are presented in Section V. The conclusions are discussed in Section VI.

THE WAVEOFF MANEUVER

Waveoff is defined as an aborted landing attempt during which the air vehicle does not touchdown [MIL-STD-3013, 2003]. There are two types of waveoff described in [MIL-STD-3013, 2003] and this document covers the on-glide slope waveoff. There are some initial conditions for waveoff maneuver. The air vehicle will be on 4º optical glide slope stabilized at V_{pa} and α_{pa}. Thrust will be as required to meet this flight condition. With a 0.7-sec delay to account for pilot reaction time when the waveoff signal is displayed, the throttle are advanced to Intermediate/Maximum-rated thrust, and speed brake (if used) retraction is initiated. Also, the following criteria stated in [MIL-STD-3013, 2003] and [Cook, Hynes and Rudowsky, 2002] are checked in the analyses for waveoff to be considered acceptable:

1. A time to zero sink speed not greater than 3.0 sec with a longitudinal acceleration of 3.0 kts/sec on a 89.8ºF day
2. Controllable angle of attack change, if required, not to exceed 0.9 CL_{max}
3. Engine spool-up characteristics must be considered.
4. An altitude loss not greater than 30 ft.

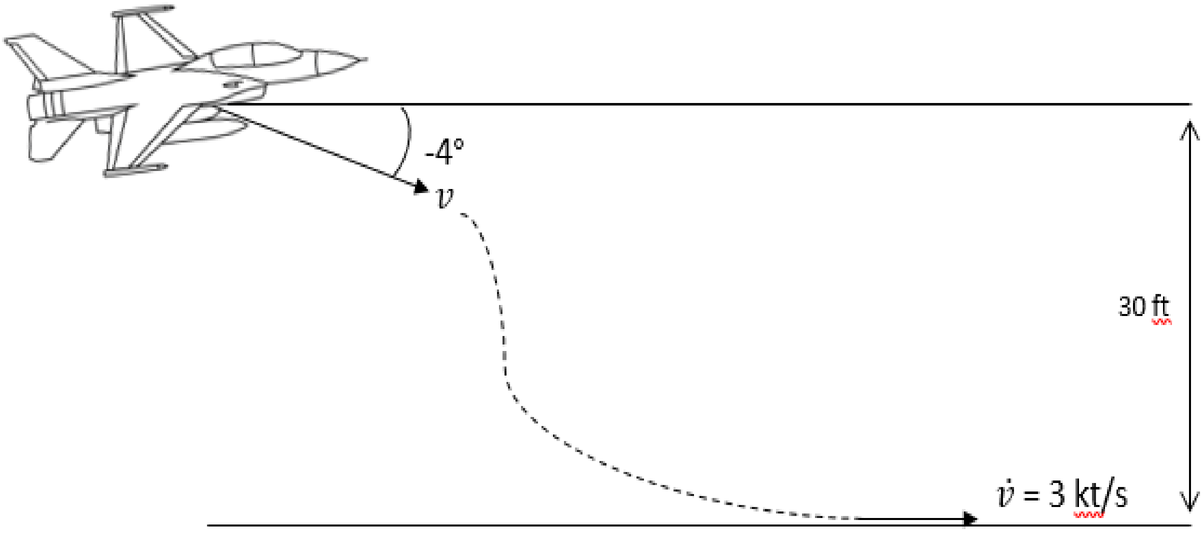

Figure 1: Waveoff Maneuver

The maneuver is complete after positive rate-of-climb has been achieved. These constraints check the aircraft safety while performing waveoff maneuver. It should be remembered that, waveoff is quite different flight phase than normal landing. In normal landing, aircraft decelerates from approach to touchdown in order to decrease ground roll distance. Nevertheless, approach speed must be lower than touchdown in naval operations. Consequently, aircraft accelerates from approach to touchdown to maintain adequate kinetic energy to recover and perform waveoff maneuver when it is necessary. Therefore, these constaints must be checked precisely. Mistakes could end up with devastating results.

AIRCRAFT MODEL SIMULATION ENVIRONMENT

Aircraft plant model representation is presented as block diagrams in Fig. 2. In this nonlinear model, the modules for atmosphere, actuator, propulsion, aerodynamics, mass & inertia, and landing gear are mathematically modeled and feed the 6-DOF equations of motion of the aircraft. The nonlinear model is integrated and built in MATLAB/Simulink environment.

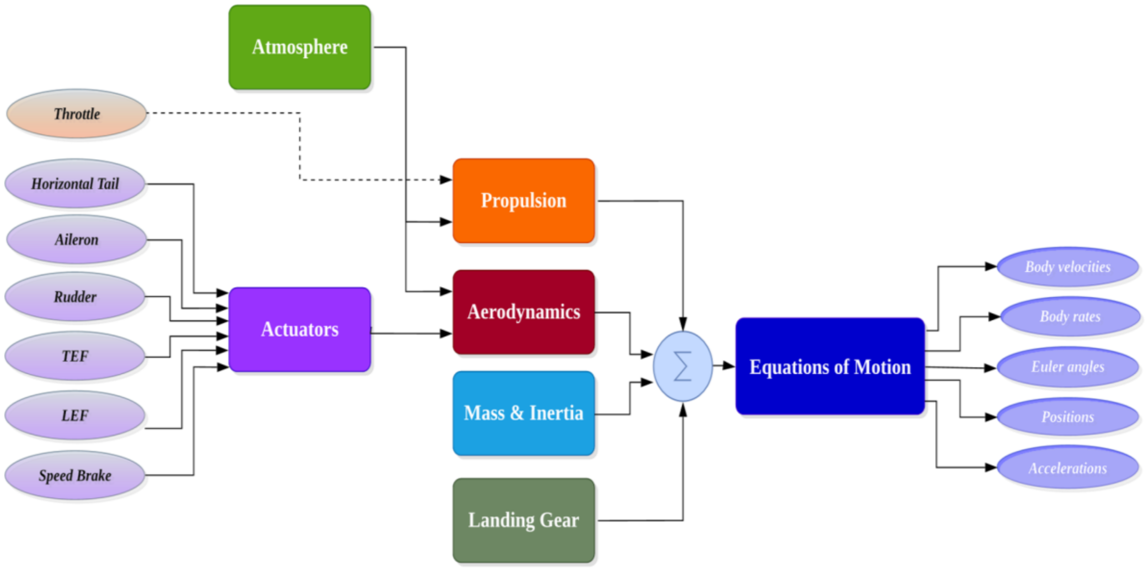

Figure 2: Aircraft Plant Model Block Diagram [Erturk and Gomec, 2020]

In this model, the aerodynamic control surfaces such as horizontal tail, aileron, rudder, trailing edge flaps, leading edge flaps and speed brakes pass through the first order actuator dynamics while the throttle setting is directly an input for the propulsion module. The atmosphere module calculates the atmospheric properties such as angle of attack, sideslip angle, pressure altitude, dynamic pressure, Mach number etc. and feeds the aerodynamics and the propulsion modules with these parameters. In the propulsion module, propulsive forces and moments are calculated based on the current Mach, angle of attack, pressure altitude, and the throttle setting. The aerodynamic forces and moments are calculated as a function of control surface inputs and the atmospheric conditions obtained by CFD solutions. The mass and inertia properties are the functions of different aircraft configurations. The gravitational forces and related inertia properties are obtained in this module. Finally, the forces and moments during the flight phases on ground are calculated by using the landing gear model. Hence, all the forces and moments calculated and are fed the 6-DOF equations of motion module. The orientations and the aircraft motions, are the outputs of the equation of motion.

6-DOF nonlinear aircraft model provides an environment for performing performance analyses at specific flight phases such as cruise, climb, descent, instant and sustain turn, takeoff, landing and waveoff. Some maneuvers require the control law systems, since the aircraft is unstable for most of the conditions in the flight envelope. Besides, maneuvers that have steady-state flight conditions can be performed without using any control feedback by using the 6-DOF aircraft model individually. An important part of this method is the identification of specific flight conditions. Trim routine should be applied with the defined flight conditions in order to achieve the steady states of the aircraft precisely. The motion of the aircraft is discretized by using the trim conditions, and, the steady maneuver can be maintained by iterating the trim routine with the updated condition. Hence, the simulation is carried out for many steady-state flight phases without the control law as long as the flight condition is determined properly. More detailed explanations of aerodynamic model of the aircraft are given in [Dursun and Erturk, 2021].

TRIM-BASED MANEUVER METHOD

The trim of the aircraft requires the steady-state motion, which means no translational and rotational accelerations acting on the aircraft. The flight conditions are selected to satisfy the constraints equal to zero, which are at least six equations derived from translational ($\dot{\boldsymbol{u}}, \dot{\boldsymbol{v}}, \dot{\boldsymbol{w}}$ in body axes system or $\dot{\boldsymbol{V}}, \dot{\boldsymbol{\beta}}, \dot{\boldsymbol{\alpha}}$ in wind axes system) and rotational ($\dot{\boldsymbol{p}}, \dot{\boldsymbol{q}}, \dot{\boldsymbol{r}}$) dynamics equations. Depending on the chosen flight, the altitude ($\dot{\boldsymbol{z}} = \mathbf{0}$) and\or the turn rate ($\dot{\boldsymbol{\psi}}$ = constant) or the pull up/push over rate ($\dot{\boldsymbol{\theta}}$ = constant) are the additional constraints to calculate the flight trim for the aircraft. In such a case that the aircraft is unstable (statically or dynamically), the control power is required to resume the desired flight condition. Hence, the trim-based maneuver method is defined to simulate the unstable flight conditions such as climb, descent, landing and waveoff without using the control law algorithms by modifying the trim conditions and the constraints and discretizing the motion of the aircraft. Furthermore, all the nonlinearities including actuators, engine properties, aerodynamics etc. are included by trimming the 6-DOF aircraft model if the nonlinearities are modeled accurately. Landing performance calculations are done with variant of this method and it is validated with piloted simulation perfectly [Dursun and Erturk, 2021].

The trim routine used for the analyses is based on the Newton-Raphson approach, which is defined for nonlinear equations set as

$$\begin{array}{ccc} f_1(\bar{x}) & = & f_1(x_1, x_2, \ldots, x_n) \\ f_2(\bar{x}) & = & f_2(x_1, x_2, \ldots, x_n) \\ \ldots & = & \ldots \\ f_n(\bar{x}) & = & f_n(x_1, x_2, \ldots, x_n) \end{array} \tag{1}$$

where

$$\bar{x} = [x_1, x_2, \ldots, x_n]^T \tag{2}$$

$$f(\bar{x}) = [f_1(\bar{x}), f_2(\bar{x}), \ldots, f_n(\bar{x})]^T \tag{3}$$

The solutions are found when all the equations in Eq. ((3) are zero. To find the solutions for the vector set in Eq. (2), the Jacobian matrix is defined

$$\boldsymbol{J}(\bar{x}) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \ldots & \frac{\partial f_1}{\partial x_n} \\ \ldots & \ldots & \ldots & \ldots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \ldots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \tag{4}$$

Hence, the solutions are obtained iteratively as

$$\bar{x}_{k+1} = \bar{x}_k - \boldsymbol{J}^{-\mathbf{1}}(\bar{x}_k) f(\bar{x}_k) \tag{5}$$

$$f(\bar{x}_{k+1}) = [f_1(\bar{x}_{k+1}), f_2(\bar{x}_{k+1}), \ldots, f_n(\bar{x}_{k+1})]^T \tag{6}$$

When the norm of Eq. (6) is less than the acceptable tolerance value, then the trim routine is terminated. The Jacobian matrix, $\boldsymbol{J}(\bar{x})$, and the state derivatives, $\dot{\boldsymbol{x}}$, are directly obtained by linearizing the 6-DOF aircraft model. In this study, the state vector is defined for steady-state conditions as

$$\bar{x} = [V, \beta, \alpha, p, q, r, \theta, \phi, \delta_T, \delta_{ail}, \delta_{HT}, \delta_{rud}]^T \tag{7}$$

and the constraints are defined as

$$f(\bar{x}) = \left[\dot{V}, \dot{\beta}, \dot{\alpha}, \dot{p}, \dot{q}, \dot{r}, \dot{\psi}, \dot{\theta}, \dot{\phi}, (\gamma - \gamma_{ref})\right]^T \tag{8}$$

where $\boldsymbol{\gamma} = \boldsymbol{\theta} - \boldsymbol{\alpha}$. The total state numbers are 12 in Eq. (7), the total equation numbers are 10 in Eq. (8). For the wing level flight condition, $\boldsymbol{\phi} = \mathbf{0}$ must be forced and "$\boldsymbol{\phi}$" is removed from the state vector. Furthermore, the speed, "$\boldsymbol{V}$", is specified for different flight conditions. Hence, the total unknowns are equal to the total specified equations. Selecting the proper initial conditions, Eq. (8) is solved for cruise, climb, descent and some phases during landing with constant approach speed.

The method is mainly based on this trim algorithm to guess parameters written in Eq. (7). Nevertheless, that equation cannot provide aircraft speed derivative, "$\dot{\boldsymbol{V}}$", which is equal to zero for the trim condition. Since waveoff analysis cannot be performed without considering deceleration/acceleration, It must be added to analysis. Thus, the trim routine is modified by removing the throttle setting, "$\boldsymbol{\delta_T}$", from the Eq. (7) and the speed derivative, from the Eq. (8) for ensuring the total unknowns must be equal to the total equations. Therefore, the solutions for constant throttle setting are obtained for with $\boldsymbol{\phi} = \boldsymbol{0}$ and specification of the speed derivative. The approach is done at constant angle of attack, "$\boldsymbol{\alpha}$", which is the preferred technique [MIL-STD-3013, 2003]. Consequently, Eq.(9) and Eq.(10) total equation numbers are equal.

$$\bar{x} = [\beta, p, q, r, \theta, \phi, \delta_{ail}, \delta_{HT}, \delta_{rud}]^T \tag{9}$$

$$f(\bar{x}) = \left[\dot{\beta}, \dot{\alpha}, \dot{p}, \dot{q}, \dot{r}, \dot{\psi}, \dot{\theta}, \dot{\phi}, (\gamma - \gamma_{ref})\right]^T \tag{10}$$

In this trim algorithm, the aircraft is released to have a translational deceleration or acceleration (nonzero $\dot{V}$) with an appropriate constant throttle setting and angle of attack. Even so, pilot increases throttle from current setting to MIL thrust to perform waveoff maneuver. This transition can be simulated by throttle map that based on engine dynamics with an acceptable time increment during maneuver.

However, to solve the Eq.(10) speed derivative must be selected reasonably. The maneuver starts at approach speed with zero acceleration, but aircraft should have longitudinal acceleration of 3 kts/sec on a 89.8 ºF day at the end of maneuver which is detailed at Section IV. Thus, first and last acceleration are known. Time is converged from making iteration of several waveoff attempts with different acceleration rates. When the aircraft has required acceleration at wing level condition, Eq.(11) is solved to get $\ddot{\boldsymbol{V}}$. Analysis is assumed that converged $\ddot{\boldsymbol{V}}$ is constant for waveoff maneuver.

$$\ddot{V} = \frac{\dot{V}_1 - \dot{V}_0}{Time} \tag{11}$$

The motion of the aircraft during waveoff is discretized with a small-time step defined as Δt. Hence, the aircraft steady states are assumed to be preserved within this time interval except the speed accelerates and the altitude drops. Simply using the sink rate formula

$$\dot{h}_j = V_j \, sin\gamma_j \tag{12}$$

where "j" represents each step in the algorithm. The altitude change with Δt is

$$\Delta h = \dot{h}_{\mathrm{j}} \, \Delta t \tag{13}$$

and the speed change with Δt is

$$\Delta \mathrm{V} = \dot{V}_{\mathrm{j}} \, \Delta t \tag{14}$$

Hence, the next flight condition after Δt is

$$V_{j+1} = V_j + \Delta \mathrm{V} \tag{15}$$

$$h_{j+1} = h_j + \Delta h \tag{16}$$

With the updated altitude and speed for Δt increment, the trim routine for Eqs. (9)-(10) is proceeded until the final speed and/or altitude is reached. Alternatively, if the altitude change is specified, Δh, the time-step Δt, is found in Eq. (13), and the trim routine is run with the same algorithm.

The speed brake, TEF and landing gear extracted cases are also included in the trim algorithm. For example, the extracting time for TEF is embedded as a function of time in the trim regarding the actuator dynamics. Furthermore, the fuel rate is the output of the propulsion module and a function of Mach, angle of attack, throttle setting and pressure altitude. For each step with Δt increment of the trim, the fuel consumption and the total weight of the aircraft are updated by using the fuel rate at that step [Erturk and Gomec,2020]. Hence, the aircraft mass configuration (c.g. and inertia) changes with time. The distance covered is also calculated by using the updated speed within the defined period. Consequently, the performance parameters are computed by simulating the algorithm with the help of trim-based maneuver method to maintain the motion of the aircraft.

RESULTS

Results of the waveoff maneuver capabilities of jet aircraft with trim-based maneuver method and its comparisons with piloted simulation results are given in this section. Analyses are done at required atmospheric conditions (89.8ºF day). Figure 3 illustrates the motions of aircraft during waveoff maneuver. The blue line corresponds to model result that provided by trim-based maneuver method and orange line corresponds to piloted simulation result in Figure 3. Some pilot actions that is not included in maneuver nature incorporated into method in order to demonstrate quasi-steady trim base method compatibility with simulation test. Normally maneuver performed with constant angle of attack since it is preferred technique [MIL-STD-3013]. However, in simulation test, pilot is not able to perform that condition. Therefore, similar angle of attack pattern with simulation test is followed with trim-based method. In addition, maneuver starts at steady condition and zero or positive acceleration rate is expected. Even so, pilot started with negative speed rate. Moreover, pilot increased acceleration rate after approaching 3 kt/sec. Nevertheless, acceleration rate pattern is also followed in the method to make appropriate comparison. It should be remembered that, acceleration rate is obtained by number of iterations in normal usage of aforementioned method.

Pilot realized waveoff signal at 0.7 sec and initiate the recovery and same action is performed with method. Throttle increases from this point with a rate that provided by engine dynamics. It is seen in the comparison that, model finished the maneuver with less altitude loss and time. The reason of this difference is horizontal tail deflected more than required value to perform recovery in piloted simulation. Consequently, less excess thrust obtained due to drag increase. Thus, flight path angle increase rate decreased in simulation test. One of the important observation in this case is pilot undesirable inputs can cause devastating results. Pilot have chance to recover in the beginning but, more pitch command than required leads to unsuccessful waveoff. On the other hand, load factor behavior for both result are significantly similar. After all, there is one thing that trim-based maneuver method cannot provide precisely is real pitch rate. The method can provide aircraft motion for corresponding flight condition with small-time step. Nonetheless, during waveoff maneuver, pilot applied significant pitch input at the beginning of the maneuver and the trim based maneuver cannot provide this first impulsive pitch command. Due to this fact, pitch rate at the beginning of the maneuver is higher than model result in piloted simulation test.

One of the most practical advantage of quasi-steady trim-based maneuver method for waveoff is obtaining maneuver applicability envelope in terms of aircraft dynamics that is shown in Figure 4. Waveoff envelope with different perspective is also given in [Johnstone, R. B., 1969]. When aircraft initiated for recovery, excess thrust increase and there are several ways to perform waveoff maneuver in those kinds of circumstances [Hui, 2016]. It is depended on pilot decisions whether to increase speed or to increase flight path angle at first. Figure 4 illustrates best and worst ways to perform the maneuver. It is clearly seen from result that, giving priority to increase flight path angle is a more reliable technique, since it ensures to recover approximately 10 ft less than worst case. Howbeit, all the path inside of the envelope can be used to perform applicable waveoff.

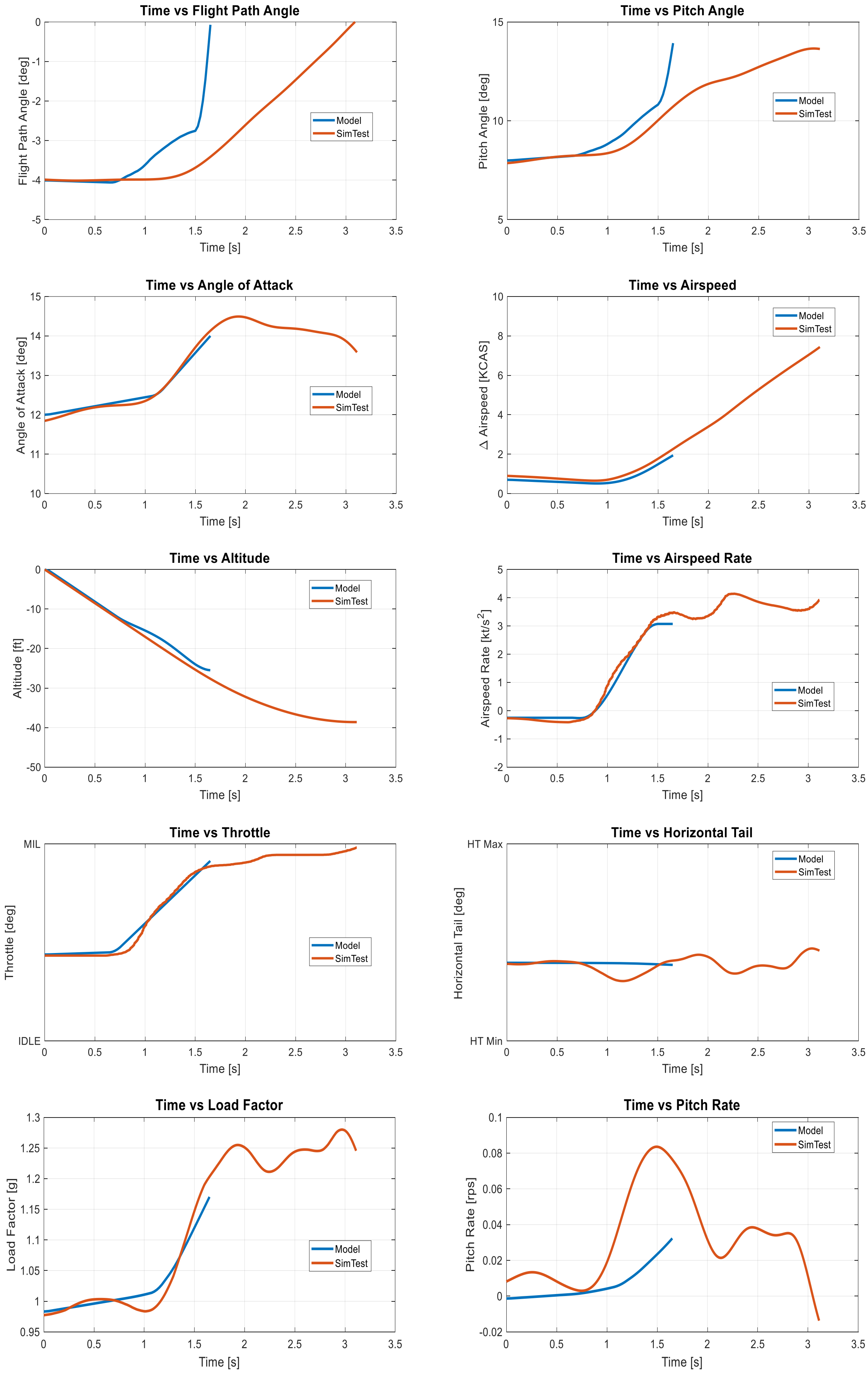

Figure 3: Simulator Test and Model Results Comparisons

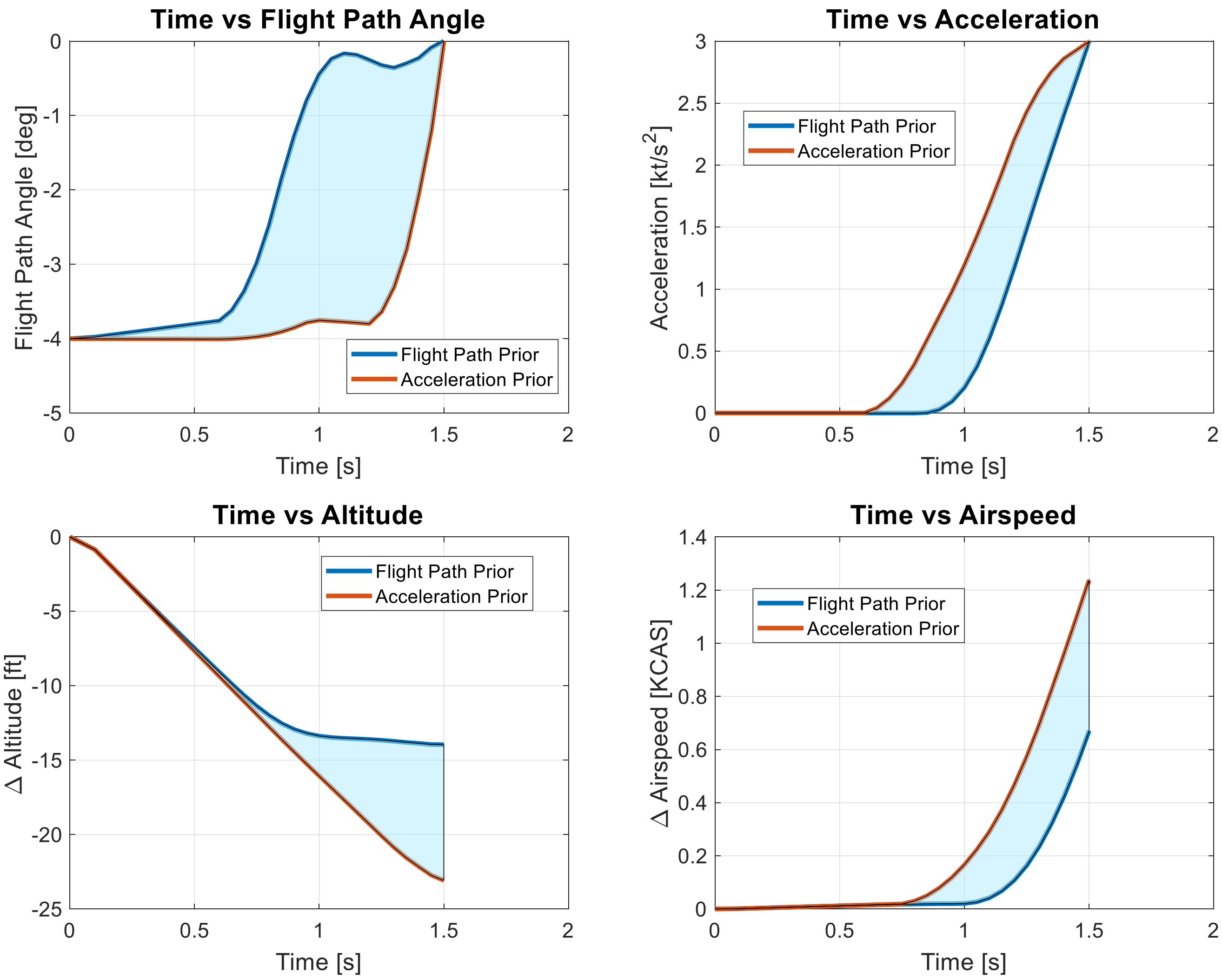

Figure 4: Waveoff Maneuver Acceptable Envelope for Constant 12º AOA

CONCLUSION

This paper investigates the waveoff maneuver capabilities of jet aircraft with trim-based maneuver method and how to perform waveoff maneuver analyses without having any flight control law systems. The simulation environment in MATLAB/Simulink is established for the 6-DOF nonlinear aircraft model. Trim-based maneuver method is discretized the aircraft motion in 6-DOF model. Even so, waveoff maneuver capability and applicable envelope can be observed. In order to increase precision, operational concerns are also investigated to understand applicability of maneuver for corresponding aircraft. Importance of acceleration motion of aircraft while performing dynamic maneuvers is the main concern of the trim-based maneuver method. According to results, waveoff maneuver's aircraft dynamics can be seen with trim-based maneuver method. Another important observation is that tuning of aircraft acceleration rate with an operational point of view increases the precision of analyses. Validation of trim-based maneuver method for waveoff maneuver is also done with piloted simulation test. Pitch rate accuracy of method can be improved in future works. This method can also be reference for a pilot while performing waveoff maneuver. Since it can provide control surface deflections to maintain corresponding aircraft condition, it will help to predict available control surface margin. Moreover, it can give feedback for flight control law algorithms in design process. Since it is a generic algorithm, it can be performed for different aircraft.

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