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F-35 STOVL Aircraft Performance Model Validation of Short Take-off Flight Test Data

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The F-35 Flight Sciences Team predicts aircraft performance with a Three Degree of Freedom (3DoF) model built from wind tunnel, computational fluid dynamics, propulsion, landing gear, and mass properties data. The team uses opportunistic flight test maneuvers from other engineering disciplines as well as dedicated aircraft performance flight test maneuvers to validate the Aircraft Performance Model for calculating Short Take-Off (STO) performance. This paper will document the methodology for assessing and validating F-35B STO flight test data. Focus will be on the evolution of F-35B modeling and simulation tools from the low-speed performance option in Lockheed Martin's Mission Analysis and Performance System (MAPS) tool. Emphasis will be placed on flight test data post-processing, atmospheric models, time-speed conversions, initial steady-state trimmed conditions, STO segment partitioning, state and controls variables, and path integration. Readers will take away knowledge of the process used to develop simulation tools that compare flight test data to aircraft performance models. This includes validation criteria for successful matching for STO performance flight test maneuvers.

Nomenclature

F_X	=	*X* component of Aircraft Body Axis Forces
F_Z	=	Z component of Aircraft Body Axis Forces
g	=	acceleration due to gravity
Iyy	=	Mass Moment of Inertia along the Y direction in the body axis
MLG	=	Main Landing Gear
M_y	=	Pitching moment in the Body Axis
NLG	=	Nose Landing Gear
q	=	pitch rate of the aircraft
$\dot{q}$	=	Pitch acceleration of the aircraft
u	=	*X* component of Aircraft Body Axis velocity
$\dot{u}$	=	*X* component of Aircraft Body Axis acceleration
V	=	Velocity in Groundspeed
w	=	*Z* component of Aircraft Body Axis velocity
$\dot{w}$	=	*Z* component of Aircraft Body Axis acceleration
W	=	Weight in the Earth Axis
X	=	*X* component of Earth Axis Distances
Z	=	*Z* component of Earth Axis Distances
X_B	=	*X* component of Aircraft Body Axis position
Z_B	=	*Z* component of Aircraft Body Axis position
X_E	=	*X* component of Earth Axis position
Z_E	=	*Z* component of Earth Axis position
α	=	Angle of Attack
β	=	Angle of Sideslip
θ	=	Pitch attitude of the aircraft
$\dot{\theta}$	=	Pitch rate of the aircraft
$\ddot{\theta}$	=	Pitch acceleration of the aircraft

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I. Introduction

Historically, flight test programs have made use of dedicated models to determine system characteristics for as-tested conditions. The objective of the F-35B Performance flight test program is to gather data that will enable validation of aircraft performance models (propulsion, aerodynamics, landing gear, etc). To accomplish this objective, the ability to measure and predict net forces and moments on the aircraft is required. Additional data is gathered on an opportunistic basis throughout System Development and Demonstration (SDD) flight testing whenever suitable parameters are recorded.

Aircraft Performance flight test maneuvers can generally be divided into two categories: steady-state (or quasi steady-state) and dynamic. A conventional takeoff is a dynamic aircraft maneuver using control surface deflections and thrust transients to provide a smooth acceleration, rotation, and liftoff characteristics. The F-35B STO increases the complexity of the conventional takeoff maneuver by adding variations in roll post thrust, core nozzle thrust vectoring, lift fan thrust vectoring, roll-post modulation, and thrust split.

In STOVL mode, the roll posts provide roll authority and stability. During the ground roll portion of a STO, roll authority is not a priority. As such, roll-post modulation is a specific variation defined for STOs where the air-flow fed to the roll posts is rerouted to the core nozzle to provide more thrust and acceleration down the runway. Thrust split for this analysis is defined as the ratio of core nozzle thrust to lift fan thrust.

$$Thrust\ Split = \frac{Thrust_{Core\ Nozzle}}{Thrust_{Lift\ Fan}} \tag{1}$$

The combination of these propulsion control effectors and legacy control surface effectors determine the pitch characteristics of the aircraft during a STO and are complex to model and analyze.

II. F-35B Aircraft Overview

The F-35B Lightning II is the Short Take-off and Vertical Landing (STOVL) variant of the Joint Strike Fighter (JSF) aircraft program, intended for use by the US Marine Corps, UK Royal Air Force and the UK Royal Navy as a replacement for the AV-8B/Harrier. It is powered by a single core engine that connects to a vertically mounted shaft driven lift fan and a thrust vectoring nozzle called the Three Bearing Swivel Module (3BSM) at the aft end of the aircraft between the horizontal and vertical tails.

The F-35Bs flight regime is divided into Conventional and STOVL mode. When the F-35B aircraft operates in the STOVL flight regime the propulsion system generates thrust exhausted through four nozzles: the main, the lift fan, and the left and right roll-post nozzles. The main or Core Nozzle (CN) has the ability to pitch downwards and yaw left and right through the 3BSM. The lift fan is powered by diverting horsepower through a driveshaft from the core engine’s low-pressure turbine via a clutch and gearbox. The lift fan exhaust can be vectored forward and aft via a Variable Area Vane Box Nozzle (VAVBN). The roll-post nozzles are located under the wings just outboard of the main landing gear. The roll-post nozzles’ downward pitch and outboard splay angles are fixed.

III. Mission Performance and Analysis System

To calculate predicted performance parameters for various maneuvers (accelerations/decelerations, climb/descents, level turns, take-offs, and landings) for various aircraft, Lockheed Martin developed the performance prediction model called MAPS. MAPS uses a system of options to evaluate mission performance, flight path performance, takeoff and landing performance, energy maneuverability characteristics, and cruise and endurance performance.

> The Mission Analysis and Performance System (MAPS) is the standard vehicle performance code used at Lockheed Martin Tactical Aircraft Systems. Used for much of the up-and-away performance analysis on the JSF program, MAPS is a large, general-purpose workstation-based batch code that typifies the traditional approach to design and analysis software.[1]

A. Path Definitions

The low-speed performance option in MAPS is restricted to flight in the vertical plane. The flight path performance model numerically integrates the equations of motion for a rigid body in the XZ plane as shown in Fig. 1. While low-speed maneuvers are highly dynamic and complex as a whole, they can be divided into less complex segments. Each segment can then be defined in terms of the state and control variables as a function of time. In summation, the maneuver can be defined by initial conditions, descriptions of aircraft behavior within each segment, and final conditions for each segment and for the path.

B. Coordinate Systems

Three coordinate systems are used: a body axis system, a wind axis system, and an earth axis system. The origins of the body and wind axis systems are located at the aircraft center of gravity. The origin of the earth axis system is located by the initial aircraft position. Figure 1 depicts these three coordinate systems.

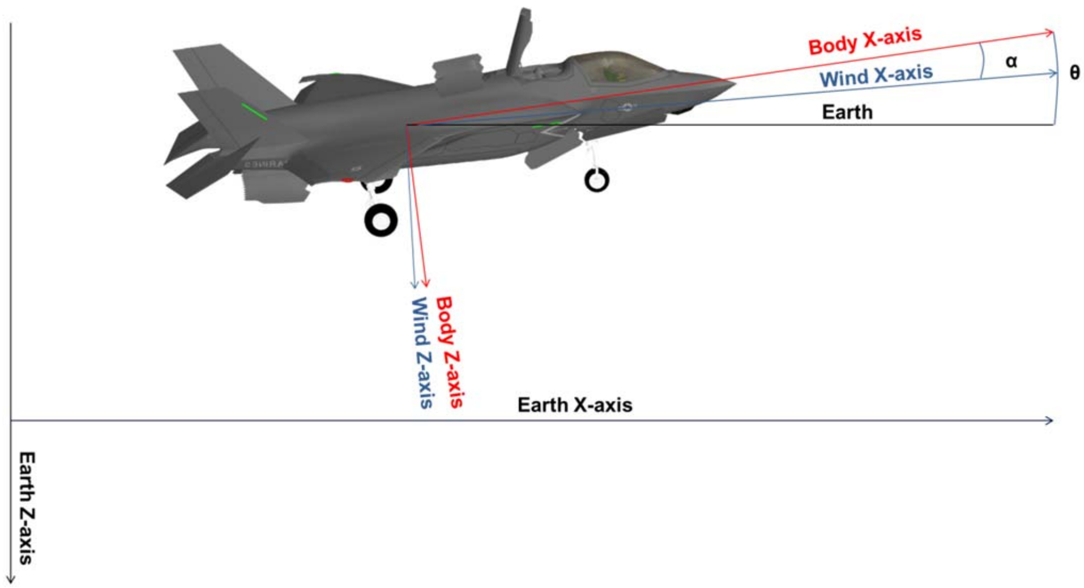

Fig. 1 Coordinate Axis Definition

C. Equations of Motion

The two-dimensional equations of motion for a rigid-body aircraft operating over a flat earth are:

$$\dot{u} = \sum F_X \frac{g}{W} - qw \tag{2}$$

$$\dot{w} = \sum F_Z \frac{g}{W} - qu \tag{3}$$

$$\dot{q} = \sum M_y / I_{yy} \tag{4}$$

$$\dot{X}_E = u \cos\theta + w \sin\theta \tag{5}$$

$$\dot{Z}_E = -u \sin\theta + w \cos\theta \tag{6}$$

$$\dot{\theta} = q \tag{7}$$

$$\dot{W} = fuel\ flow \tag{8}$$

Thus, once the forces and moments being applied to the aircraft are known, these equations can be integrated to give the resulting flight path.

D. Forces and Moments

The equations of motion require the sum of the forces in the body coordinates. Consequently, the forces are defined in both their "natural" coordinate system and the body coordinate system. All forces from the earth and wind coordinate systems are then converted to the body axis system.

The four sources of forces and moment on the aircraft are aerodynamic forces (lift and drag), propulsive forces (thrust and ram drag), weight force, and landing gear forces (ground and friction forces). Figures 2 to 4 represent these forces on the aircraft.

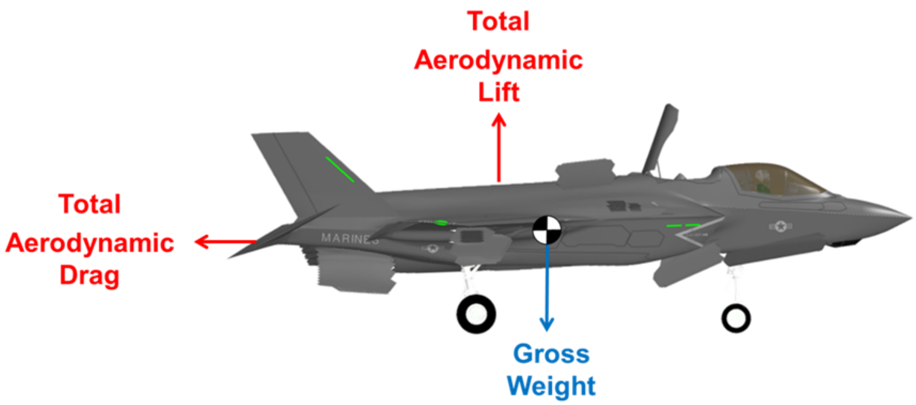

Fig. 2 Aerodynamic and Weight Forces on the F-35

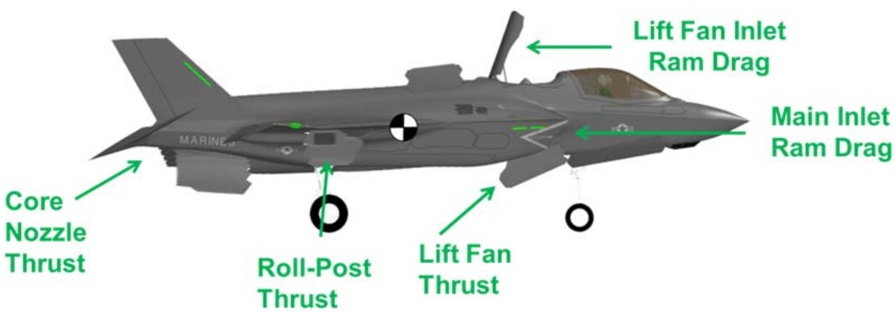

Fig. 3 Propulsive Forces on the F-35

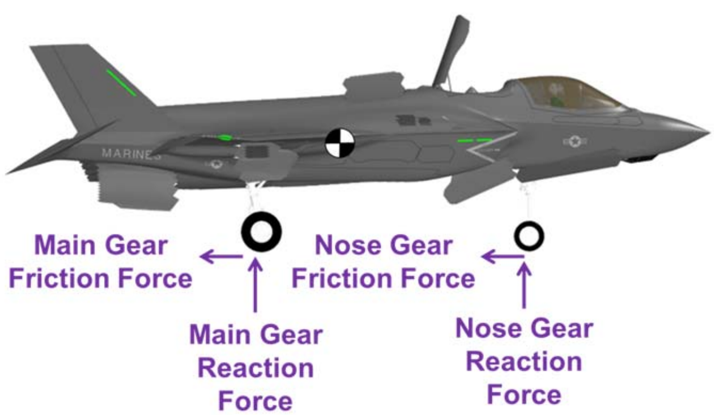

Fig. 4 Landing Gear Forces on the F-35

E. MAPS Short Take-off Evolution

The low-speed performance option in MAPS was developed before STOVL capable jets were in development. As such, the model lacked the functionality for a lift fan, a full vectoring 3BSM, and roll post nozzles. The Lockheed Martin Performance Team developed a model to utilize the lift fan thrust vectoring, core nozzle vectored thrust, and roll-post nozzles, while keeping the flight path numerical integration of the equations of motion in the XZ plane.

IV. Performance Model

A. Short Take-off Segment Definitions

To model a STO, the Lockheed Martin Performance Team partitioned the STO into separate segments for the purposes of either changing control effector guidance or to measure the state of the aircraft at various points throughout the STO. Figure 5 demonstrates one variation and presents the respective termination variables, and the termination conditions that must be met to integrate to the next segment. These segments are derived to generate performance predictions and are not necessarily tuned to match flight test values.

Segment #	Segment Name	Segment Description	Termination Variable	Termination Condition	Termination Value
1	Throttle Slam	Advance Throttle	Time	>	#####
2	Wheel Skid	Skid to Brake Release	Time	>	#####
3	Roll-Post Modulation On	Accel to Rotation Speed	KCAS	>	#####
4	Rotate_A	Rotation Initiation	Time	>	#####
5	Rotate_B	Rotate to Nose Gear Liftoff	Nose Gear Reaction Force	<	#####
6	Rotate_C	Reverse 3BSM to Main Gear Liftoff	Main Gear Reaction Force	<	#####
7	Fly Away 2s	Trim w/3BSM Climb for 2s	Segment Time	>	#####
8	Fly Away 50'	Trim w/3BSM Climb to 50ft	Main Gear Height	>	#####
9	Fly Away 100'	Trim w/3BSM Climb to100ft	Main Gear Height	>	#####

Fig. 5 Short take-off segment definitions

In this example the ground roll, rotation, and flyaway portions of the STO are each divided into 3 separate segments:

Ground Roll:

1. The "Throttle Slam" segment is defined as the throttle slam from idle power to military power (MIL) or maximum (MAX) power and based on the assumed time it takes the pilot to advance the throttle. MAX Power does not include afterburner, but an elevated thrust level compared to MIL power.
2. The "Wheel Skid" segment is defined by the assumed time taken for the pilot to hold full throttle position while removing brake pressure from 100% to 0%.
3. The "Roll-Post Modulation On" segment of the ground roll is defined by the aircraft accelerating down the runway until it reaches the speed to initiate rotation.

Rotation:

1. The "Rotate_A" segment is defined by the time to initiate a core nozzle pulse to force a nose-up pitching moment on the aircraft.
2. The "Rotate_B" segment is defined as the farthest aft the nozzle reaches to induce aircraft rotation until the reaction force on the nose-gear reaches zero and subsequently the model reaches nose-gear liftoff.
3. The "Rotate_C" segment is defined as the final on-ground rotation segment in which the main gear lifts off. The segment terminates when the reaction force on the main-gear reaches zero.

Flyaway:

1. The "Flyaway 2s" segment is defined by the time to 2 seconds after take-off. The Flyaway segments are only used to analyze the state of the aircraft.

2. The “Flyaway 50’” segment is defined by a 50 foot increase in altitude from rotation initiation.
3. The “Flyaway 100’” segment is defined by a 100 foot increase in altitude from rotation initiation.

B. State Variables

To integrate the path, the pitch variables in the XZ plane as well as their derivatives must be known. Each state variable is then recalculated at the new time increment using the state derivative and integrated over the entire time slice. The model fully defines the state of the aircraft using 8 state variables and each state’s time derivative, as listed in Table 1.

State Variable	State Variable Derivative
X_E – X position of the aircraft in the earth axis.	V_{XE} = X velocity of the aircraft in the earth axis
Z_E – Z position of the aircraft in the earth axis.	V_{ZE} = Z velocity of the aircraft in the earth axis
θ = Pitch attitude of the aircraft in the vertical plane.	$\dot{\theta}$ = Pitch rate of the aircraft in the vertical plane
$\dot{\theta}$ = Pitch rate of the aircraft in the vertical plane	$\ddot{\theta}$ = Pitch acceleration in the vertical plane
V_{XB} = X velocity in the body axis	$\dot{V}_{XB}$ = X Acceleration in the body axis
V_{ZB}= Z velocity in the body axis	$\dot{V}_{ZB}$ = Z Acceleration in the body axis
MLG_{ZE} = main gear Z position in the earth axis	$M\dot{L}G_{ZE}$ = main gear Z velocity in the earth axis
NLG_{ZE} = nose gear Z position in the earth axis	$N\dot{L}G_{ZE}$ = nose gear Z velocity in the earth axis

Table 1. State Variables and Derivatives

C. Segment Controls

The F-35B Performance Model defines the following as control effectors used to vary the longitudinal and vertical forces in the pitch plane on the aircraft: leading-edge flaps, trailing-edge flaps, rudders, elevators, roll-post modulation index, brakes, power setting, lift fan thrust vector, core nozzle thrust vector, and thrust split.

Each control parameter is defined by a nominal value, minimum value, maximum value, rate of change, and a figure of merit to guide the controller.

The guidance policies used for the controller are as follows:

1) H - Hold the previous value of the control
2) I – Increase the control value at rate limit
3) D – Decrease the control value at rate limit
4) C- Hold the control value to a chosen constant
5) G – Use the control value defined by the control schedule
6) FT – Use the flight test recorded control value
7) F – Set the control using linear feedback to achieve the desired value (figure of merit)

All guidance policies with the exception of the “F” policy are open-loop policies. The utilization of the F policy for any control effector takes the model from an open-loop state to a closed-loop state by matching the desired pitch path using a figure of merit (usually pitch acceleration).

The “F” policy takes the chosen effector and finds a control value that will create the proper forces and moments to generate the proper pitch acceleration and subsequent pitch rate and pitch attitude to match the desired pitch path. It is then forced to find a control value to match the pitch path. To further illustrate this, Fig. 6 provides an example control effector guidance matrix:

Segment #	Segment Name	Segment Description	Rudder	Leading Edge Flaps	Trailing Edge Flaps	Brakes	Roll-Post Modulation	Power Setting	Thrust Split	Lift Fan Vector Angle	3BSM Vector Angle	Elevator
1	Throttle Slam	Advance Throttle	G	G	G	H	I	I	G	G	G	G
2	Wheel Skid	Skid to Brake Release	G	G	G	H	I	I	G	G	G	G
3	Roll-Post Modulation On	Accel to Rotation Speed	G	G	G	C	I	I	G	G	G	G
4	Rotate_A	Rotation Initiation	G	G	G	C	C	I	F	G	D	D
5	Rotate_B	Rotate to Nose Gear Liftoff	G	G	G	C	C	I	F	G	I	I
6	Rotate_C	Reverse 3BSM to Main Gear Liftoff	G	G	G	C	C	I	F	G	I	I
7	Fly Away 2s	Trim w/3BSM Climb for 2s	G	G	G	C	C	I	G	H	F	G
8	Fly Away 50'	Trim w/3BSM Climb to 50ft	G	G	G	C	C	I	G	H	F	G
9	Fly Away 100'	Trim w/3BSM Climb to100ft	G	G	G	C	C	I	G	G	F	G

Fig.6 Control Effector Matrix

In the example control effector matrix, the ground roll segments all have open-loop policies. No “F” policy is selected for any effectors and therefore the model is integrating along the path without trying to match any pre-defined pitch characteristics.

For the rotation portion of the STO, the thrust split effector is switched to the “F” policy changing the model from an open-loop system to a closed-loop system. The model is now forcing thrust split to vary in order to match the nominal desired pitch path.

Lastly, the flyaway portion of the STO utilizes the 3BSM vector angle effector to close the loop of the system, while the other effectors utilize open-loop guidance policies.

D. Pitch Capture Time

When utilizing the “F” policy to create a closed-loop system, the pitch capture time adds another level of guidance by giving the model a specified time step to match the desired pitch path. The pitch path is computed using a cubic trajectory tangent to the current pitch attitude/pitch rate state and to the desired final pitch attitude/pitch rate state. This pitch capture time is the time step that the cubic polynomial must use to find a tangent pitch attitude and pitch rate equal to the desired pitch path. Figures 7 to 9 depict the performance model incrementally closing in on the desired pitch attitude. The pitch attitude, pitch rate, and pitch acceleration polynomials are defined below.

$$\theta(t) = at^3 + bt^2 + ct + d \tag{9}$$

$$\dot{\theta}(t) = 3at^2 + 2bt + c \tag{10}$$

$$\ddot{\theta}(t) = 6at + 2b \tag{11}$$

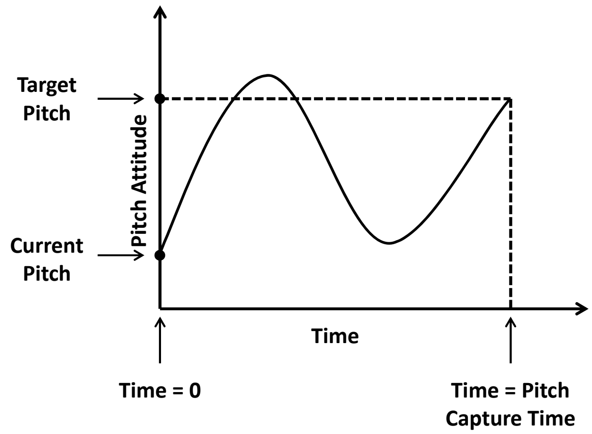

Fig. 7 Cubic Pitch Polynomial at Time = 0

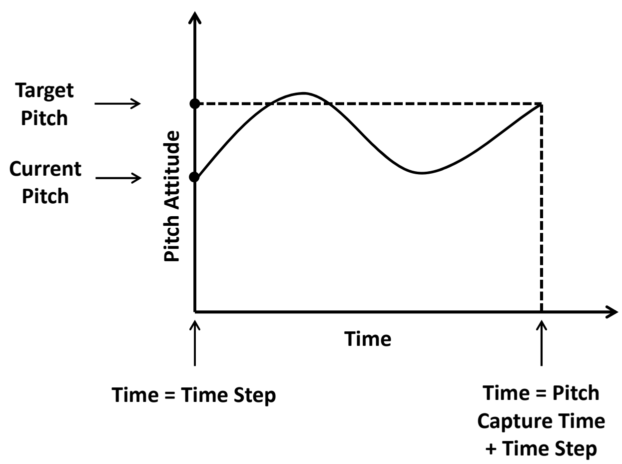

Fig. 8 Cubic Pitch Polynomial at Time = time step

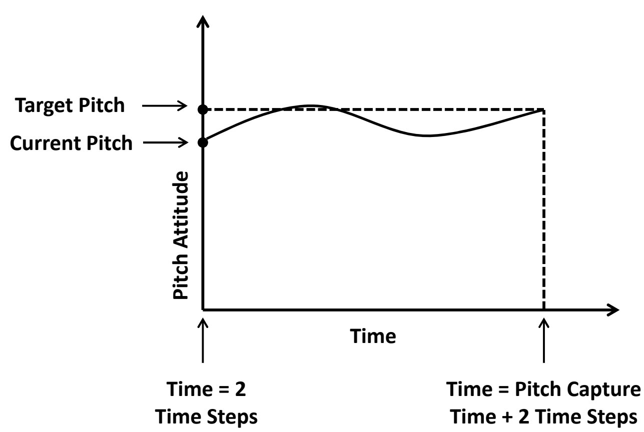

Fig. 9 Cubic Pitch Polynomial at Time = 2 time step

The model then derives the coefficients a, b, c, & d so that the cubic and quadratic polynomial is tangent to the current $\theta(t)$ and $\dot{\theta}(t)$ values of the performance matching tool and tangent to the desired $\theta(t)$ and $\dot{\theta}(t)$ values over a time constant (pitch capture time) defined by the user. This allows the user to define how aggressively the control effector should work to achieve the desired pitch path.

E. Linear Control

When the "F" policy is chosen to close the control loop, the system utilizes a proportional controller with the control effector as the controller with appropriate gain, the aircraft as the plant, and the pitch acceleration as the input and output of the system. Figure 10 depicts a closed-loop block diagram for one step in the performance model integration.

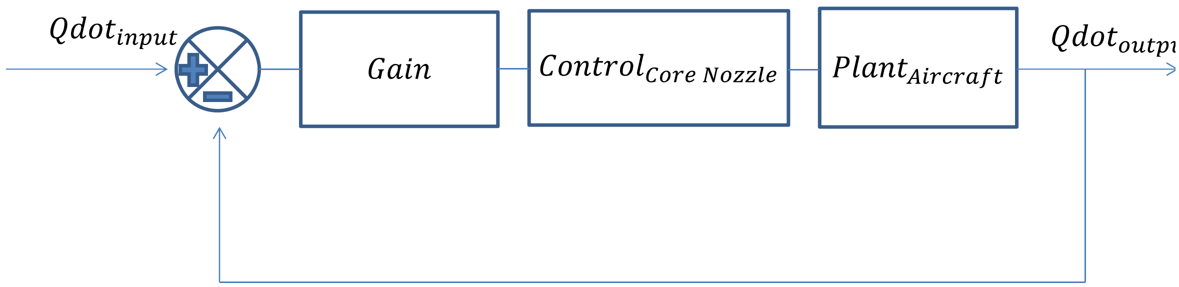

Fig. 10 Block Diagram of Example Closed Loop System

V. STO Flight Test Procedures

To ensure accurate comparisons with the Performance Model, pilots attempt to execute a STO with as little roll or yaw input as possible. The 3DoF model only operates in the pitch axis and this pilot technique ensures all significant forces and moments are accounted. Specifically, the pilot will attempt to remain wings level with minimal control inceptor inputs between rotation and 100 feet Above Ground Level (AGL). To minimize variability in STO rotation characteristics, pilots must perform an automated rotation, using one of two methods developed for the F-35B: Button STO or Automatic (Auto) STO.

The Button STO is executed by the pilot by releasing the brakes, accelerating the aircraft to the desired rotation speed, and initiating the STO rotation via a button press. The Auto STO is executed by the pilot entering the target STO rotation distance into the on-board display. He or she then initiates brake release, and the aircraft accelerates to the desired distance and automatically initiates rotation. With the aforementioned STO types, the Performance Flight Test points cover a varying range of power setting, target gross weight, fuselage station center of gravity, rotation speed, field altitude, and temperature.

VI. Flight Test STO Start and End Conditions

The Lockheed Martin Performance Team defines the beginning of a STO at brake release, more specifically, when the left and right main gear brake pressures fall below 100% brake pressure. The team then considers the STO terminated when one of the following three conditions have been met: reduction of Engine Thrust Request (ETR), bank angle greater than 3°, or gear-up command.

VII. FTAPA

FTAPA, or Flight Test Aero Performance Application, is a Lockheed Martin software application used to calculate Aerodynamic and Performance parameters, and to calculate in-flight thrust for flight test data. This software tool also integrates the flight path history and calculates α, β, and airspeed based on wind and air data sources. The output of this tool is fed into the performance model for all flight test maneuvers that are analyzed.

VIII. Post-Flight Matching Model

There are currently two methods used by the F-35 Performance Team to analyze flight test data. The first is the "Post-Flight" Method, which generally utilizes flight test recorded control effector positions as open loop controllers in the performance model. This method allows the Performance Team to compare model differences in unpowered aerodynamics, powered aerodynamics, mass properties, landing gear model, or propulsion with the actual behavior of the aircraft during a STO.

A. Initialization Steady State Trim

To properly model the flight path, it is necessary to establish initial values for the integration state variables. The model's runway altitude is placed at the same pressure altitude as measured on the aircraft. Effector positions are set to initial values recorded during flight test. Mass properties such as fuselage and waterline Cg, Iyy, and total weight of the aircraft are set to initial flight test conditions.

A numerical solver is utilized to iterate on the remaining integration variables. A search is performed on the landing gear compression to drive the total moment around the center of gravity to zero.

B. Post-Flight Model Segment Controls

The Post-Flight Model is defined by 8 segment definitions that model the ground roll, rotation, and flyaway characteristics as shown in Fig. 11.

Segment #	Segment Name	Segment Description	Rudder	Leading Edge Flaps	Trailing Edge Flaps	Brakes	Roll-Post Modulation	Power Setting	Thrust Split	Lift Fan Vector Angle	3BSM Vector Angle	Elevator
1	Throttle Slam	Advance Throttle	FT	FT	FT	FT	I	FT	FT	FT	FT	FT
2	Wheel Skid	Skid to Brake Release	FT	FT	FT	FT	I	FT	FT	FT	FT	FT
3	Roll-Post Modulation On	Accel to Rotation Speed	FT	FT	FT	FT	I	FT	FT	FT	FT	FT
4	Rotate_A	Rotation Initiation	FT	FT	FT	FT	C	FT	FT	FT	F	FT
5	Rotate_B	Rotate to Nose Gear Liftoff	FT	FT	FT	FT	C	FT	FT	FT	F	FT
6	Rotate_C	Reverse 3BSM to Main Gear Liftoff	FT	FT	FT	FT	C	FT	F	FT	FT	FT
7	Fly Away 50'	Trim w/3BSM Climb to 50ft	FT	FT	FT	FT	C	FT	F	FT	FT	FT
8	Fly Away 100'	Trim w/3BSM Climb to100ft	FT	FT	FT	FT	C	FT	F	FT	FT	FT

Fig. 11 Post-Flight Model Control Effector Matrix

The rudder, elevator, leading-edge flaps, trailing edge flaps, brake pressure, power setting, and lift fan vector angle of the model all use flight test recorded values for the given groundspeed. Roll-post modulation logic is set from off to on and maintained throughout ground roll, rotation, and flyaway. The roll-post air flow is fed through the core-nozzle during ground roll then fed to the roll-posts at rotation and flyaway. The core nozzle vector angle uses flight test values for the ground roll and flyaway portions of the STO. For the rotation portion of the STO, the core nozzle control policy is set to linear feedback to find a pitch acceleration that corresponds to the same pitch attitude and pitch rate of flight test aircraft. During take-off and flyaway, thrust split is set to linear feedback to match the pitch characteristics recorded in flight test.

The first 3 segments of the STO, which define the ground roll, are controlled in an open-loop manner. No effector is trying to match the pitch path. For segments 4 through 8, the core nozzle and thrust split were chosen as the closed-loop effectors through extensive trial and error. The pulse of the core nozzle that initiates rotation is a large contributor to the pitching moment on the aircraft and is a natural choice for a closed-loop effector.

The differences in the performance model whether from unpowered aerodynamics, powered aerodynamics, mass properties, landing gear model, or propulsion, create different forces and moments on the modeled aircraft relative to the flight test aircraft. These differences in forces and moments create a difference in pitch acceleration and subsequently differences in pitch rate and pitch attitude.

C. Time-Speed Conversion

Flight test data is recorded in the time domain with time as the independent variable and every flight test variable as dependent variables. It is desired to have the model accelerate with the same groundspeed as the flight test data, as most aircraft performance analysis is performed in the speed domain. If there are differences in the acceleration characteristics of the model, the time trace will not match as well as a speed trace. One solution to this issue is to match the flight test time with the true groundspeed of the aircraft. Because the flight test true ground speed monotonically increases with flight test time, a one-to-one match of unique control surface deflections for each specific groundspeed can be found. Anytime a control effector has the "FT" guidance policy selected, this time-speed conversion matches the correct flight test control effector value at the model's groundspeed.

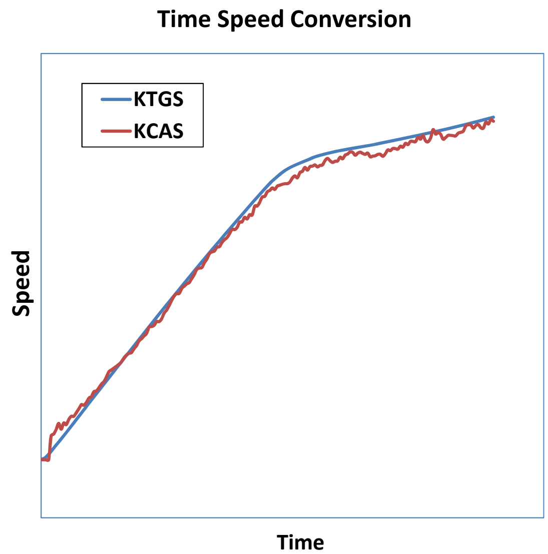

Fig. 12 Flight test speed as a function of time

Another option for converting time to the speed domain is through calibrated airspeed. However, calibrated airspeed is not necessarily monotonically increasing with time in the same manner as true groundspeed, as seen in Fig. 12. This creates multiple control effector positions for a given airspeed and causes the model to lose fidelity. One solution is to use true groundspeed as the monotonic conversion from time to speed and then to convert true groundspeed to calibrated airspeed through an atmospheric model.

D. Atmospheric Model

To effectively capture the aerodynamic properties of the model as it integrates through the path, an atmospheric model must be employed. Using flight test instrumentation measured on the aircraft, headwind is recorded as a function of distance, as seen in Fig. 13.

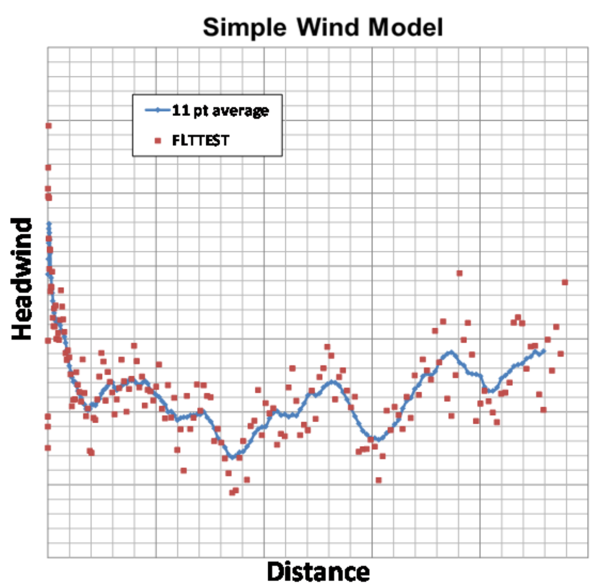

Fig. 13 Flight test headwind as a function of distance

An 11-point average is incorporated to smooth out the scatter of the measured raw data. This simplified wind model is then used to map airspeed with groundspeed and effectively calculate the aerodynamic properties on the aircraft at any point in the path integration.

E. Trace Comparisons

Figures 14 to 16 are time history integrations with the performance model trace in red and the flight test measurements in blue.

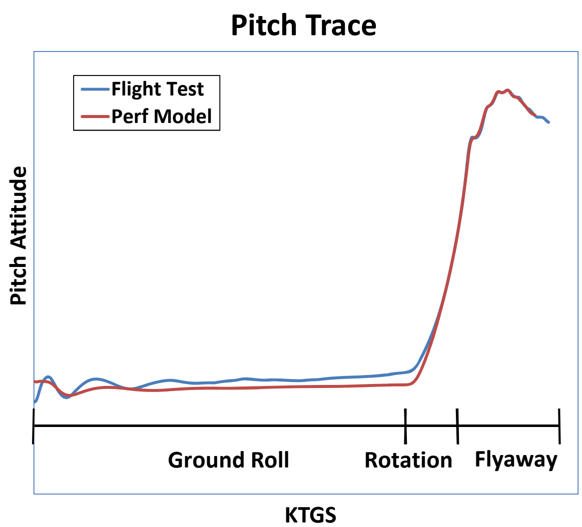

Fig. 14 Post-Flight Model Pitch Trace

Figure 14 indicates the post-flight model does not match the pitch oscillations during the ground roll. Again, the model is using an open-loop control scheme during this portion of the STO and is directly inputting flight test recorded values into the model. At rotation, the model goes from open-loop to closed-loop and uses the core nozzle to match the pitch attitude of the flight test aircraft. After the model "catches up" to the flight test pitch attitude, it holds the pitch trace very tightly through take-off and flyaway.

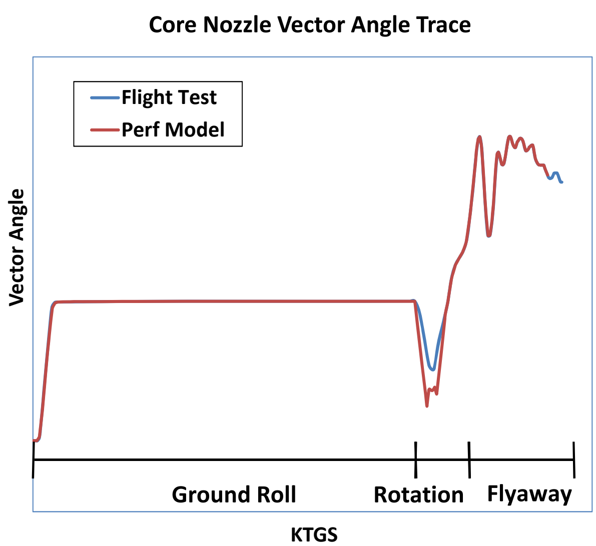

Fig. 15 Post-Flight Model Core Nozzle Vector Angle Trace

Through the ground roll, the core nozzle matches flight test feedback values. Once the aircraft reaches rotation speed, the core nozzle is pulsed to initiate rotation. At this point the core nozzle is set to closed-loop linear feedback. As stated earlier, the differences in the model, whether from unpowered aerodynamics, powered aerodynamics, mass properties, landing gear model, or propulsion, all create different forces and moments on the model aircraft than the flight test jet. These differences in force and moment create a difference in pitch acceleration and subsequently a difference in pitch rate and pitch. The core nozzle vector angle delta seen between flight test and the model at rotation is due to the model's core nozzle attempting to counteract all of these differences in force and moment. After the pulse to create rotation, the core nozzle is set back to flight test feedback values for take-off and flyaway.

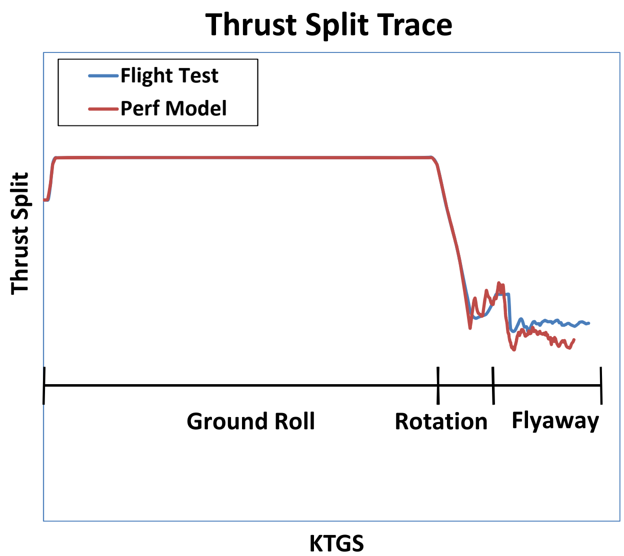

Fig. 16 Post-Flight Model Thrust Split Trace

Thrust split is set to follow flight test inputs during ground roll and rotation. It is then set to closed-loop linear feedback at take-off and flyaway. This is a highly transient regime of the STO (due to multiple effectors following the control laws) and the model exhibits oscillations until the flight test thrust split reaches a nominally steady value. Despite this highly transient region, the pitch capture seen in Fig. 14 still matches tightly throughout flyaway.

IX. Pre-Flight Matching Model

The second flight test analysis method is the "Pre-Flight" Method. This method involves using the initial conditions recorded during flight test, the control schedules defined by the control laws for all open-loop effectors, and the predicted pitch attitude and pitch rate as the figure of merit for the closed-loop effectors.

Only STOs flown at optimal performance conditions (optimal rotation speed to reach 50 feet altitude in the shortest distance) can be compared to the model. If the flight test aircraft does not initiate rotation at the rotation speed that the model would predict, then the match will have a noticeable offset in the speed domain. Figure 17 depicts a pitch trace where the flight test aircraft rotated at the recommended rotation speed. Figure 18 depicts a pitch trace where the flight test aircraft rotated before the recommended rotation speed. The value of this analysis is to verify that the pre-test predicted STO performance is indicative of actual performance.

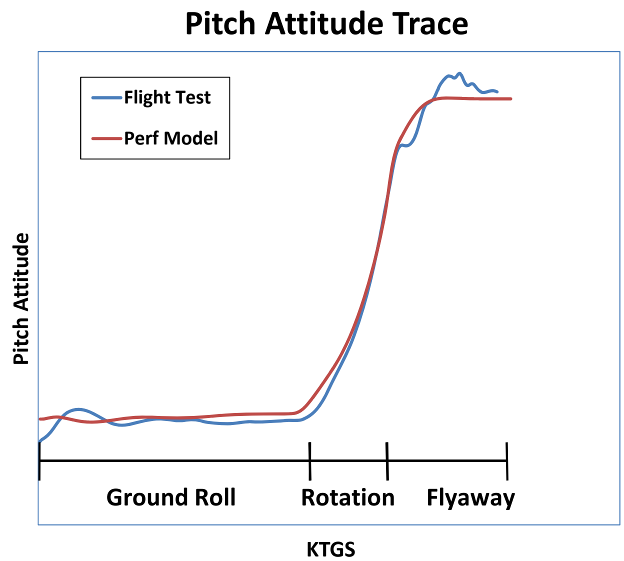

Fig. 17 Pitch Trace at Recommended Rotation Speed

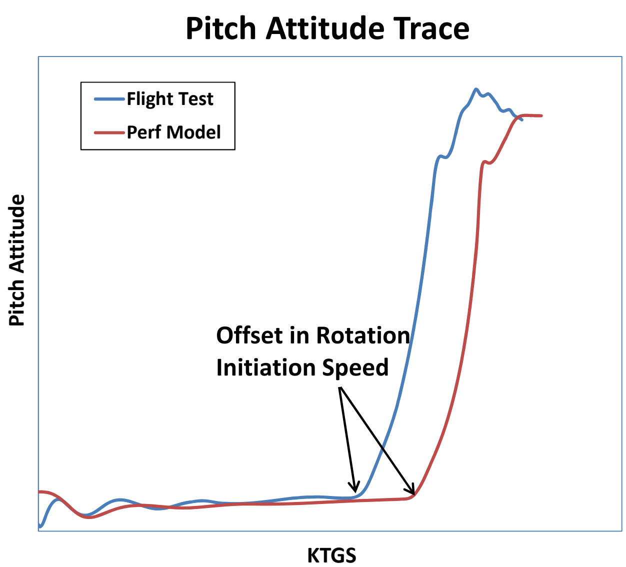

Fig. 18 Pitch Trace before Recommended Rotation Speed

X. Conclusion

The F-35 Aircraft Performance Team has been tasked with validating the powered and unpowered aerodynamics, mass properties, landing gear, and propulsion databases to effectively predict aircraft performance parameters for any condition. Future tasks will include developing a model that can reference flight test values in the distance domain for ship-based STOs, due to the importance of distance on ship-based performance parameters. As more flight test data is analyzed and trends are found, empirical corrections can be made to either flight test instrumentation or the aircraft model itself. Currently the model does an excellent job of representing the aircraft's performance characteristics with only the use of a single linear feedback controller. The F-35 Aircraft Performance Team is optimistic with the current progress and evolution of the model.

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