

Application of Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations Using NASA's X-57 Maxwell

Casey L. Denham *

NASA Langley Research Center, Hampton, VA 23681

Mayuresh Patil †

Georgia Institute of Technology, Atlanta, GA 30332

Christopher J. Roy ‡

Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

Natalia Alexandrov §

NASA Langley Research Center, Hampton, VA 23681

A framework to estimate the performance and associated uncertainty of modified configurations of certified aircraft is applied to the X-57 Maxwell aircraft. In previous theoretical studies, the framework was shown to predict performance and uncertainty bounds accurately. The X-57 Maxwell is an experimental aircraft designed to demonstrate the benefits of distributed electric propulsion through a series of four incremental modifications to a Tecnam P2006T aircraft. The available models and data are first shown to be within the application domain of the framework. We then apply the framework to two X-57 Maxwell modifications. We compare the estimated performance and associated uncertainties against the airworthiness criteria. The results indicate that the framework is a promising tool for the certification by analysis workflow. We expect the framework to reduce and supplement the flight testing required to show compliance to airworthiness certification criteria for a modified configuration.

I. Nomenclature

C_*	=	generalized aerodynamic coefficient
C_*^{base}	=	value of generalized coefficient from baseline model for the nominal configuration
u, v, w	=	body-axis velocities in the x, y, and z directions, respectively
u_0	=	aircraft trim velocity
p, q, r	=	body-axis angular rates, about the x, y, and z directions, respectively
δa	=	aileron deflection
δe	=	elevator deflection
δr	=	rudder deflection
δC_*^{tun}	=	additional correction due to tuning of modified configuration model
δC_*^{base}	=	change in baseline model due to modified configuration, difference between modified configuration and nominal configuration
$\delta C_*^{UQ} _{mod}$	=	uncertainty bounds from model form uncertainty for modified configuration, evaluated about the modified model
ΔC_*^{tun}	=	correction due to model tuning, difference between tuned model and baseline model for nominal configuration

*Aerospace Technologist - Aerospace Vehicle Design and Mission Analysis, Aeronautics Systems Analysis Branch, MS 442, AIAA Member

†Professor of the Practice, Guggenheim School of Aerospace Engineering, AIAA Associate Fellow

‡Professor, Crofton Department of Aerospace and Ocean Engineering, AIAA Associate Fellow

§Principal Investigator, Autonomous Integrated Systems Research Branch, MS 233, AIAA Associate Fellow

$\Delta C_*^{UQ} _{base}$	=	uncertainty bounds from model form uncertainty for nominal configuration, evaluated about the baseline model
$\Delta C_*^{UQ} _{tun}$	=	uncertainty bounds from model form uncertainty for nominal configuration, evaluated about the tuned model
θ	=	pitch angle
ϕ	=	roll angle

II. Introduction

As novel aircraft are introduced, either through completely new designs or modifications to existing aircraft, accurately predicting the flight performance continues to be vitally important. Flight testing is the current standard for determining whether the system meets minimum requirements of airworthiness, safety of flight, and risk [1]. Organizations tasked with airworthiness certification, such as the Federal Aviation Administration (FAA) and Naval Air Systems Command (NAVAIR), are required to consider modifications to previously certified aircraft, such as a change in wing characteristics, as an entirely separate aircraft for the purposes of certification [1–3]. It is not always preferred to spend the time and cost of flight tests for these modifications, especially because they are based on existing aircraft that already have available data. For novel aircraft utilizing new technology such as electric propulsion, using a similar aircraft as a baseline for performance comparison prior to the flight, can reduce the risk for initial flight testing. The X-57 Maxwell project has taken this approach by designing a demonstrator that steps through a series of modifications, from a currently certified general aviation airplane to a fully electric aircraft with modified geometry [4].

There is currently significant interest in certification by analysis - where analysis and simulation supplement or replace flight testing in the certification process. In 2021, the AIAA Certification by Analysis Community of Interest published a set of recommended practices [5]. In particular, the community is interested in using analysis and simulation to model modifications to previously certified aircraft, including the associated uncertainties [6]. Even with limited or no flight test data, the modified configurations must still be accurately modeled and simulated in order to meet the standards of airworthiness with the required level of confidence [6]. Certification by analysis is already commonly done in the nuclear industry, due to high risks and costs associated with full-scale testing, but it is in its infancy in the aerospace industry [7]. Uncertainty quantification is important for certification by analysis, particularly uncertainty due to the form or structure of the selected model, because it enables consideration of conditions where experimental data are limited [8–10].

This paper uses a framework based on uncertainty analysis and non-deterministic simulations to estimate the flight performance of modified aircraft configurations without requiring flight test data on the modified configuration. The framework, described in Refs. [11] and [12], uses knowledge of the unmodified, nominal configuration to assist in the simulation of the modified configuration. The framework consists of two methods to estimate the modified aircraft dynamics and the uncertainties of the modified aircraft dynamics. Both methods use aspects of the nominal system, account for changes due to the modification, and are used to perform non-deterministic simulations. Non-deterministic simulations are simulations which take into account uncertainty and other non-constant or known variables, allowing variation between simulation runs. This framework is designed to be independent of the source or quality of the data, as well as the model form or accuracy (for example, a linear model created using CFD data). The estimated performance generated from the framework then could be used to reject unsuitable configurations or otherwise inform the flight test process.

Because the X-57 Maxwell is one of the first electric aircraft and serves as a concept demonstrator, special emphasis is being placed on the certification and regulatory aspects that need to be created for electric aircraft. The first step in the process is identifying the current standards and regulations for the aircraft, using a small civil aviation aircraft as the reference vehicle [13]. Although many of the flight performance requirements remain unchanged, significant changes would be required in standards for engines and propellers [13]. The X-57 Maxwell project works with regulators to identify regulatory barriers and develop new standards to enable the use of innovative technologies [14, 15]. An additional goal of the certification review process is to identify and pair new technologies to the corresponding regulations to assist in the adoption of the new technologies within the aviation community [15].

We start with a brief overview of the framework from Refs. [11] and [12], followed by an introduction to the X-57 Maxwell aircraft. We then apply the framework to the already defined "Mods" of the X-57 Maxwell, using a combination of simulation and flight test data, demonstrating each step in the process. The framework results will be validated against flight test data for the original, unmodified configuration (Mod-I). We present the predicted performance for Mod-II and Mod-III, which do not yet have flight test data available. The paper concludes with an assessment of the

results and possible future applications and extensions with this methodology.

III. Approach

The uncertainty of greatest interest is model form uncertainty, or uncertainty due to the difference between the true system and the mathematical representation of the system, brought on by lack of knowledge of the system [9]. The limited availability, poor quality, or inherent noise of the data sources, such as inertial measurement units (IMUs) or air data probes, can contribute to additional uncertainty associated with the model.

A. Generation of Baseline Models

The first model that is generated for the nominal configuration is the baseline model, which is later corrected and modified. Ideally, the same method should be used for developing models for the nominal configuration and any modified configurations. However, CFD data and wind tunnel data may be easily obtained for an aircraft, but flight test data are not usually available for all configurations. For the nominal configuration, an example aerodynamic coefficient is denoted by C_*^{base} . Baseline models for any modified configurations are also created.

B. Generation of Tuned Models

We next generate a tuned model for the nominal configuration. It uses the most accurate data available, generally parameter estimation (also known as model tuning) of flight test data. Although these data are more accurate, they may not exist for all configurations. Therefore, a tuned model can typically only be created for the nominal configuration. This tuned model will generally have the same model form (linear or non-linear) as the baseline model, but that is not a requirement. The difference between the tuned model of the nominal configuration and the baseline model of the same configuration is represented by ΔC_*^{tun} . Using example artificial data, these notional components are shown for a lift coefficient curve in Fig. 1.

Often, this model will be generated using parameter identification of flight test data but could include higher fidelity CFD or wind tunnel data. Common parameter estimation techniques include equation error method, output error method, and filter error method, described in Ref. [16]. For this work, the output error method was chosen due to the ease of implementation.

C. Estimation of Uncertainty

To calculate the model form uncertainty, the model is evaluated at each time step of the flight test data or higher fidelity simulation data and is then compared to the data values. The process yields a series of time-independent errors for each timestep, as shown in Fig. 2. Uncertainty is estimated using 95% confidence intervals on the mean error between the higher fidelity data and the lower fidelity baseline or tuned model for each equation of motion, as described in Hale et al. and Montgomery:

$$\hat{y}(x_0) - t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 x_0' (X'X)^{-1} x_0} \leq \mu_{y|x_0} \leq \hat{y}(x_0) + t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 x_0' (X'X)^{-1} x_0} \quad (1)$$

Here $\hat{y}(x_0)$ is the model response about the aircraft state x_0 , $t_{\alpha/2, n-p}$ is the Student's t-distribution for $100(1-\alpha)$ confidence interval with $n - p$ degrees of freedom where n is the number of samples and p is the degree of the polynomial), $\hat{\sigma}^2$ is the sample standard deviation, $\mu_{y|x_0}$ is the mean error of the model response at the aircraft state, and X is the matrix of observed data. The bounds are shown in Fig. 2 as red lines. Note that the bounds are modified to always include zero error to prevent changes to the model form or tuning. Because the bounds are dependent upon the state of the aircraft, they can be correlated to specific states, allowing for smaller bounds where there are more data and larger bounds where data are sparse, as in Ref. [17]. Because the bounds grow exponentially as the aircraft state moves away from the available data, prediction for aircraft states far from observed values can lead to high uncertainty.

The uncertainty can be calculated for both the baseline and tuned models, creating two different estimates, as shown in Figs. 3 and 4. In Fig. 3, the uncertainty is calculated and applied about the baseline model, shown in black, generating larger uncertainty bounds due to the differences between the lower fidelity data used to create the baseline model and the flight test data. Figure 4 illustrates the case where the uncertainty is calculated and applied about the tuned model, shown in orange. These uncertainty bounds are smaller because the tuned model is closer to the observed data than the baseline model.

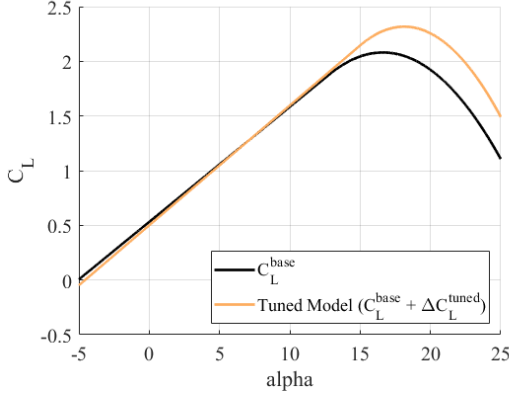


Fig. 1 Baseline model (black) and tuned model (orange), illustrated using example data.

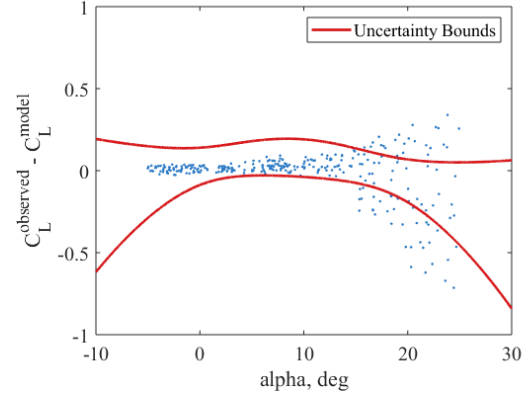


Fig. 2 Calculation of uncertainty bounds (red), using differences between model and observed data (blue).

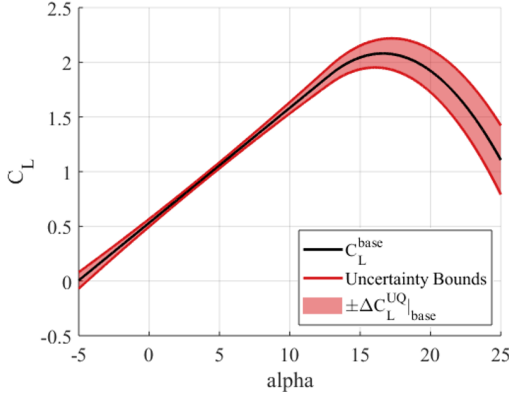


Fig. 3 Uncertainty calculated about the baseline model.

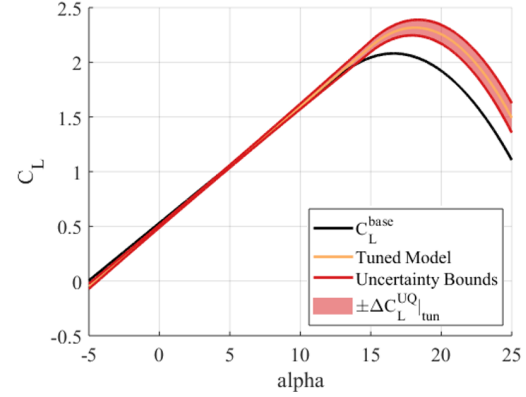


Fig. 4 Uncertainty calculated about the tuned model. Note that the uncertainty is smaller because the tuned model is closer to the observed data.

D. Combining Baseline Models, Tuned Models, and Uncertainty

Using the nomenclature described in Ref. [11], C_* represents a generic aerodynamic coefficient, such as the Coefficient of Lift. The nominal configuration of this model can be described using a combination of the baseline model C_*^{base} , model tuning ΔC_*^{tun} , and uncertainty ΔC_*^{UQ} . Since we can calculate uncertainty from both the baseline and tuned model, there are two related models:

$$C_*^{baselinewithUQ} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} \quad (2)$$

and

$$C_*^{tunedwithUQ} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} \quad (3)$$

Equation 2 describes the case where the uncertainty is calculated about the baseline model, $C_*^{UQ}|_{base}$, while Equation 3 describes the case where the uncertainty is calculated about the tuned model, $C_*^{UQ}|_{tun}$.

When we describe a modified aircraft configuration, additional terms appear. After including additional model tuning and uncertainty quantification, the final model for the modified configuration can be written in two different ways, corresponding to Equations 2 and 3:

$$C_*^{baselinewithUQ,mod} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \pm \delta C_*^{UQ}|_{base} \quad (4)$$

$$C_{*}^{tunedwithUQ,mod} = C_{*}^{base} + \Delta C_{*}^{tun} \pm \Delta C_{*}^{UQ}|_{tun} + \delta C_{*}^{base} + \delta C_{*}^{tun} \pm \delta C_{*}^{UQ}|_{tun} \quad (5)$$

where δ indicates the change due to modification in the configuration, δC_{*}^{base} is the change to the baseline model due to the modified configuration, δC_{*}^{tun} is the additional correction due to model tuning for the modified configuration, and δC_{*}^{UQ} is the additional uncertainty for the modified configuration. While δC_{*}^{base} can be obtained by comparing lower fidelity data, such as wind tunnel or CFD data, of the nominal and modified configurations, δC_{*}^{tun} , $\delta C_{*}^{UQ}|_{base}$, and $\delta C_{*}^{UQ}|_{tun}$ cannot be calculated without higher fidelity data for the modified configuration, such as flight test data, which is often unavailable.

Using the prior knowledge of the nominal configuration, we propose two methods to estimate the uncertainty of the modified configuration [11]. The methods differ in the approximation of δC_{*}^{tun} and δC_{*}^{UQ} but do not require parameter tuning and uncertainty quantification for the modified configuration. The methods are intended for small and large modifications, respectively.

E. Tuned Model Method

The first method to estimate the model and uncertainties of the modified configuration, called the Tuned Model Method, approximates the total uncertainty for the modified configuration as the uncertainty for the nominal configuration, with model tuning for the nominal configuration applied to the modified configuration. That is, no additional model tuning is assumed to be needed for the modified configuration, and the uncertainty bounds of the nominal configuration are assumed valid for the modified configuration. This method is intended for small modifications, where the modification does not have a large change to the model dynamics, resulting in a similarly small change to the true model tuning. Using Equation 5, this is equivalent to setting δC_{*}^{tun} and $\delta C_{*}^{UQ}|_{tun}$ equal to zero.

In order to generate the updated model used for non-deterministic simulations, the final model can be written as

$$C_{*} = C_{*}^{base} + \Delta C_{*}^{tun} \pm \Delta C_{*}^{UQ}|_{tun} + \delta C_{*}^{base} \quad (6)$$

In other words, the baseline model for the modified configuration is updated using the change from the nominal configuration to the modified configuration (δC_{*}^{base} , shown as blue in Fig. 5) and the tuning correction from the nominal configuration (ΔC_{*}^{tun} , shown in orange). The additive process is shown in Fig. 5 using example artificial data, resulting in the updated model, represented as the black starred line. The uncertainty bounds for the nominal configuration calculated using the tuned model ($\Delta C_{*}^{UQ}|_{tun}$, shown in red) are then applied to this model to obtain updated uncertainty bounds for the modified configuration. This process is shown in Fig. 6 for the example data, where the uncertainty bounds are applied to the updated model calculated in the previous figure. In this case, the uncertainty bounds are small because they are calculated about the tuned model.

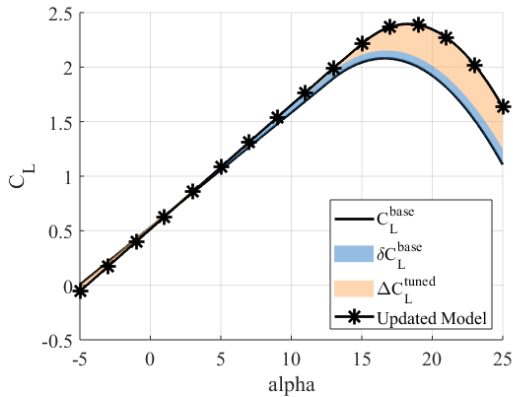


Fig. 5 Generation of updated model for the modified configuration using Method 1 with example data. The changes due to the modification, in blue, and the tuning correction term, in yellow, are added to obtain the updated model.

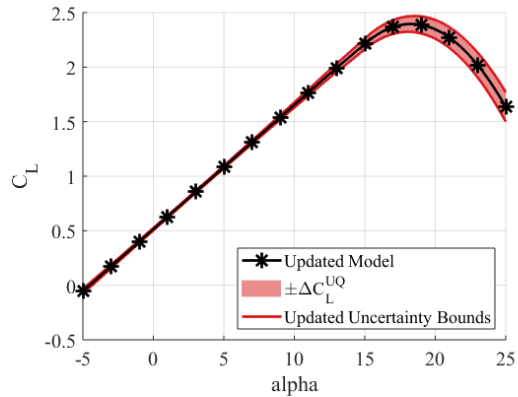


Fig. 6 Addition of the uncertainty bounds, red, from the nominal configuration to the updated model of the modified configuration using Method 1, showing the updated uncertainty bounds using example data.

F. Baseline Model Method

The second method of estimating uncertainties of the modified configuration approximates the total uncertainty for the modified configuration as the uncertainty that would occur if there were no tuning for the nominal configuration. This is equivalent to stating that the model tuning correction for the nominal configuration is no longer valid and that the total uncertainty for the modified configuration can be approximated as the uncertainty for the nominal configuration with no tuning. This method is intended for larger modifications where the change in dynamics is substantial and a greater change in the tuning correction would be expected. The updated model for the modified configuration can then be written as

$$C_* = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \quad (7)$$

For this method, the baseline model for the nominal configuration, in black, has the change due to the modified configuration (δC_*^{base} , shown as blue in Fig. 7) added to create the updated model, shown as the black starred line using the example data. Then, uncertainty bounds ($\Delta C_*^{UQ}|_{base}$, shown in red) are created using flight test data and the baseline model of the nominal configuration and then applied to this updated model. This creates much larger uncertainty bounds about the updated model, as shown in Fig. 8.

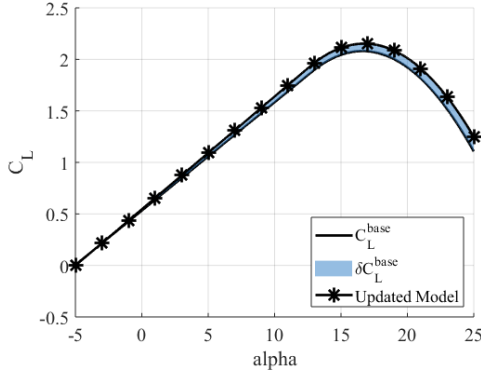


Fig. 7 Generation of updated model for the modified configuration using Method 2. The updated model for the modified configuration has only the changes due to the modification, in blue, added to the baseline model of the nominal configuration.

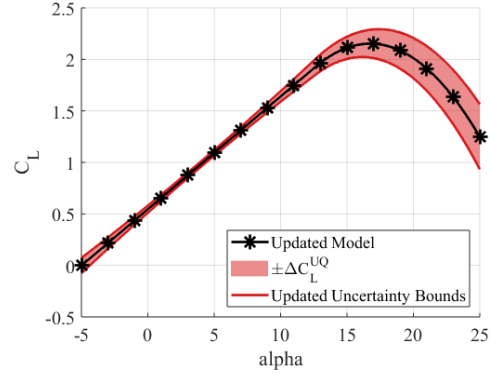


Fig. 8 Calculation of the total uncertainty for the modified configuration using Method 2, with example data. The total uncertainty is the uncertainty from the baseline model.

IV. X-57 Maxwell

The X-57 Maxwell, shown in Fig. 9, is one of NASA's current X-Plane demonstrators. It features an all-electric design with distributed electric propulsion. X-57 is one of the first manned aircraft with distributed electric propulsion, having 12 spanwise propellers along the wing to improve low-speed performance, as well as two more traditional propellers at the wingtips used for propulsion [4]. This design aims to demonstrate at least a 3.5x reduction in energy consumption compared to a conventionally powered aircraft at cruise [4]. X-57 Maxwell also aims to explore the certification and regulatory requirements for an all-electric aircraft, demonstrating that such an aircraft can be flown safely while meeting performance standards [4]. The approach is to introduce a series of modifications to an existing aircraft, incrementally transforming it into an electric aircraft and ultimately including distributed electric propulsion. The Mods are shown in Fig. 10.

The Mods make the X-57 Maxwell a good candidate to explore the use of our framework from Refs. [11] and [12] to predict aircraft performance for modified configurations. Here, we focus on the Mod-II configuration, which has a relatively minor modification from the original Tecnam P2006T aircraft (the change from gas powered to electric motors), as well as the Mod-III configuration, which has a more substantial modification from the original aircraft (an updated wing and the inclusion of 12 spanwise mounted propeller nacelles [4]). For this research, we are interested in the flight performance at cruise, so the spanwise propellers meant for high-lift and high-angle-of-attack conditions included in Mod-IV would not be in use [4].

As a research aircraft, the X-57 Maxwell has a large amount of wind tunnel and CFD data for Mods II through IV [19–21]. Much of these data have been put into 6-degree-of-freedom aircraft simulations using MATLAB®’s Simulink® Software [21]. Flight test data are also available for the baseline Tecnam P2006T aircraft, which serves as the Mod-I configuration [21]. However, flight test data for the Mod-II through Mod-IV configurations have not yet been collected, with flight testing planned in the future.



Fig. 9 An artist’s rendering of the X-57 Maxwell aircraft in flight, shown in the Mod IV Configuration.

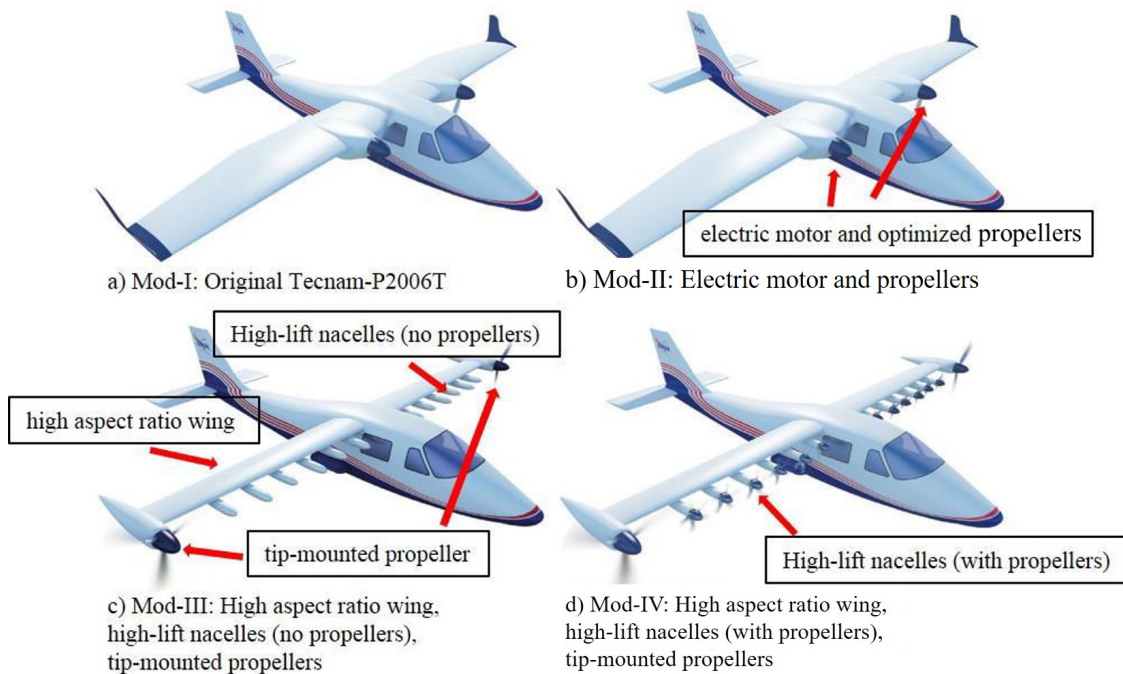


Fig. 10 Incremental modifications of the X-57 Maxwell, from the Tecnam P2006T to the complete distributed electric propulsion aircraft [19].

V. Application and Results

A. Generation of Baseline Models from Simulation

Simulation models of the X-57 Maxwell configurations were previously generated using a combination of CFD and wind tunnel tests [19–21]. The simulations have previously been used as a comparison to flight test data of the Tecnam P2006T, which also serves as the Mod-I configuration [20]. A linear 6-degree-of-freedom model was generated by linearizing the X-57 Maxwell simulations for the Mod-I, Mod-II, and Mod-III configurations. Figure 11 shows a comparison of this baseline linear model for the Mod-I configuration to the Tecnam P2006T flight test data, with the flight test data in black and the evaluated baseline model in blue. In addition to being a first-order linear model, which excludes many of the higher-order dynamics seen in the flight test data, there is significant noise in the flight test data, particularly in the velocity components. Recall that this baseline model is used only as a reference and the tuned model, generated from analysis of the flight test data, is used as the more accurate model.

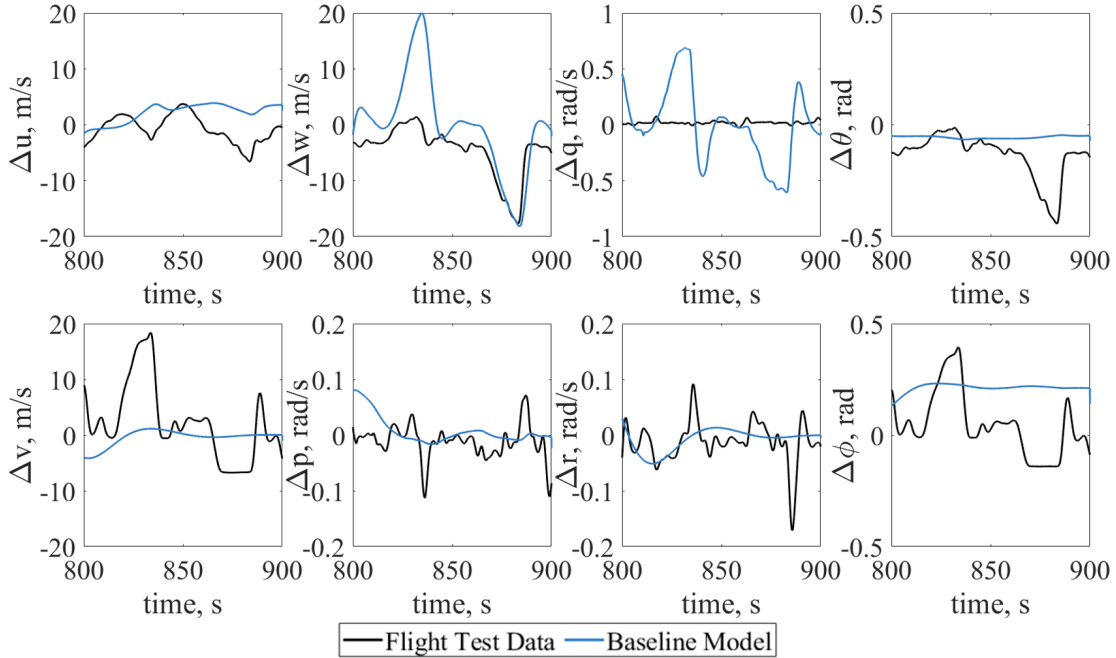


Fig. 11 Comparison of the baseline model for the Mod-I configuration to flight test data of a Tecnam P2006T.

B. Generation of Tuned Model Using Flight Test Data

A tuned model of the aircraft dynamics is created using system identification of flight test data to capture any mismatch between the simulation and the actual performance of the aircraft. Although any system identification method could be used, the output error method was used for this research, using adapted scripts from Ref. [16].

For the X-57 Maxwell, flight test data from a Tecnam P2006T flight serve as the tuning data for the Mod-I configuration. This flight test included a number of different maneuvers relevant to system identification, including doublets, and also includes repeat maneuvers, enabling this type of analysis. The tuned model also has a linear 6-degree-of-freedom model form, to facilitate matching with the baseline model. Figure 12 shows a comparison between the tuned model and the Tecnam P2006T flight test data, for a segment of flight test data which contained the maneuver. However, exact wind conditions, velocity measurements, and throttle control data were not collected, all of which lead to increased noise and decreased model accuracy in the longitudinal states - Δu , Δw , Δq , and $\Delta \theta$. This is seen in Fig. 12, where the tuned model does not include many of the high frequency dynamics seen in the flight test data. An improved tuned model could be generated by redoing the flight tests with additional sensors and by using a higher-order non-linear model form.

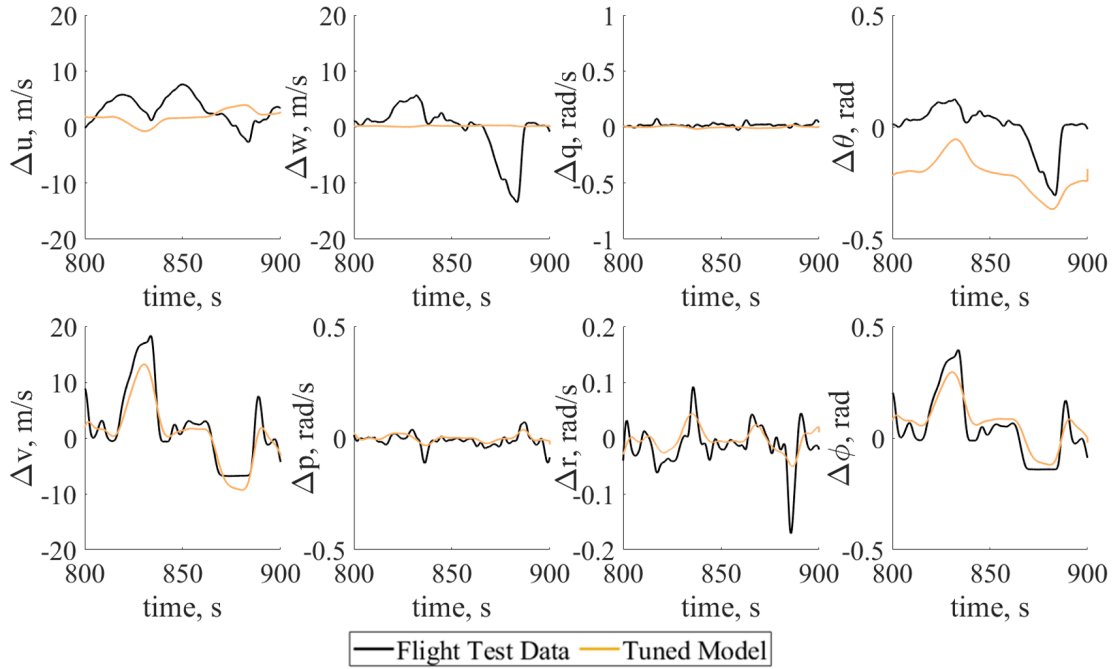


Fig. 12 Comparison of the tuned model for the Mod-I configuration to flight test data of a Tecnam P2006T, for a section of flight test data containing a maneuver.

C. Uncertainty Quantification

Model form error is estimated by calculating the difference between the aerodynamic model and flight test data. Various sources of noise can affect this calculation, including unsteady wind and sensor noise. Even if these sources are not exactly known, the difference serves as a reasonable estimate of the actual model form error.

For the X-57 Maxwell aircraft, the Tecnam P2006T flight test data were compared to the models previously described. Figure 13 shows these errors for vertical acceleration, $\Delta \dot{w}$, as well as the uncertainty bounds calculated using Eq. 1. The errors, shown as blue dots, are calculated at each timestep by comparing the model result and the observed flight test data. The uncertainty bounds are calculated using Eq. 1, using the observed flight test data, as a function of each aircraft state. This creates multi-dimensional uncertainty bounds, which are shown in Fig. 13 as red slices centered about the trimmed position. Because the flight test data contain a variety of different maneuvers and aircraft states, the uncertainty bounds are able to remain steady for a large range of states instead of growing exponentially due to lack of data. Most of the uncertainty bounds show little dependence on aircraft state, with the exception of forward velocity Δu . Because forward velocity often is heavily impacted by wind and the flight test data do not include throttle measurements, this correlation is not unexpected.

D. Non-Deterministic Simulation

A single simulation is conducted using the initial condition and control surface inputs from the validation data segment while non-deterministic simulations are conducted by including uncertainty and repeating the simulation many times. Using the previously calculated uncertainty bounds, uncertainty in the states is added at each timestep, dependent on the current state and control inputs. The simulation also includes a turbulent wind component, which adds additional realistic uncertainty to the simulation to more closely match the flight test data, where there is a significant unknown wind component. To fully capture the dynamics and uncertainty of the aircraft design, multiple independent simulation runs are combined to create a range of expected performance. Bounds of the estimated flight performance are calculated by taking 95% of the combined simulation data. Convergence analysis of the simulation results is performed to demonstrate that the number of simulation runs achieved suitable convergence, indicated by the steady-state uncertainty bounds remaining within 0.1% with the addition of additional simulation runs.

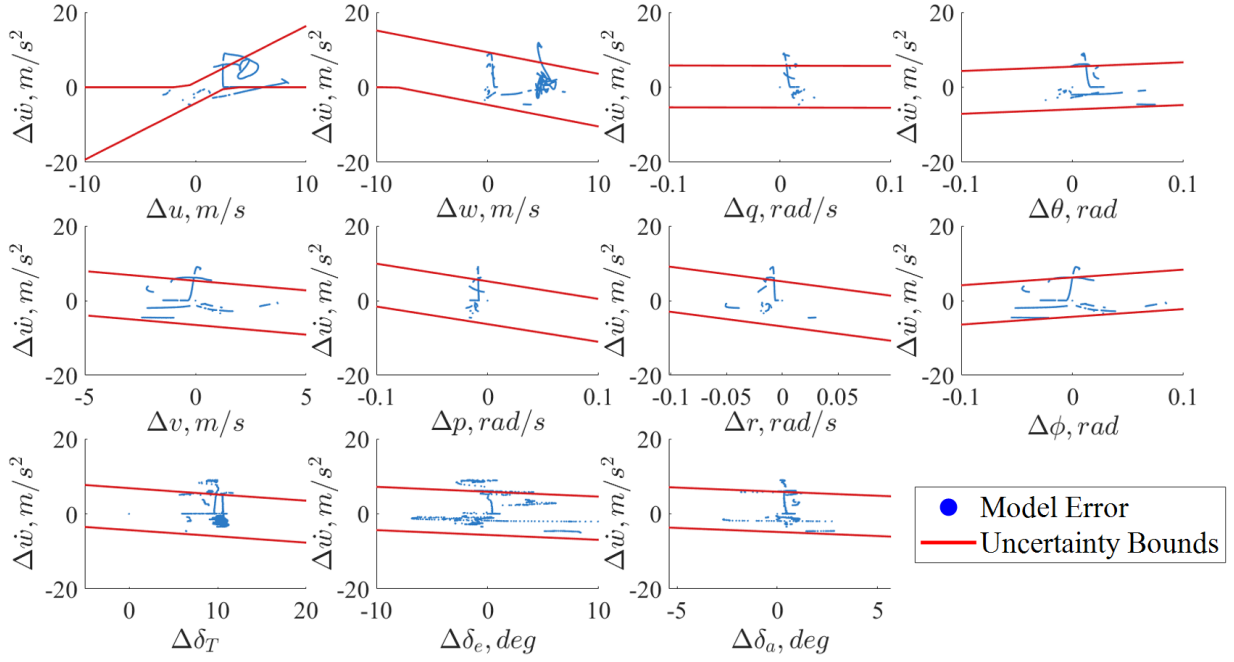


Fig. 13 Calculated uncertainty bounds (red) and model form error (blue) for the tuned X-57 model, for the $\Delta\dot{w}$ state, corresponding to vertical acceleration.

E. Validation of Nominal Model (Mod-I)

It is important to validate that the updated model generated by the framework is close to the flight test data. For the X-57 Maxwell data, a different segment of flight test data not used for model tuning or uncertainty quantification is compared to the model. Shown in Fig. 14, the simulation results using the updated model, in blue, are compared to the flight test data, in black. With the exception of the forward velocity, Δu , most of the states have small differences between the two, most likely representing a small mismatch in the trim conditions. It is also important to confirm that the uncertainty bounds generated from non-deterministic simulations, shown in red, contain the majority of flight test data for this segment indicating that the bounds account for variation as illustrated in Fig. 15. These uncertainty bounds are much larger than the observed dynamics of the aircraft because of the unknown turbulent wind component in the flight test data. There is good agreement between the model and flight test data, compared to previous analysis in Ref. [11], indicating that the model is suitable for the nominal Mod-I configuration. As further improvements and refinements are made to the model, it is expected that the agreement with the flight test tuning will improve and the conservativeness of the uncertainty bounds will decrease.

F. Prediction of Performance for Mod-II and Mod-III

Because flight tests for the X-57 Maxwell Mod-II or Mod-III configurations have not yet been conducted, the flight performance can only be predicted, not validated. This predicted performance could then be used to assist in the planning of future flight tests, validating aerodynamic models, or developing additional modifications.

For the Mod-II configuration, which features the original Tecnam wing with electric motors and updated propellers, the baseline model is quite similar to the baseline model for the Mod-I configuration. This similarity is shown in Fig. 16, where a simulation using the model for the Mod-II configuration, shown in green, is nearly the same as the model for the nominal Mod-I configuration, shown in blue. This small difference, equivalent to $\delta C_x^{base}|_{modII}$, indicates that the Tuned Model Method, described in section III.E is adequate for the Mod-II configuration. Using the Tuned Model Method, the updated model and associated uncertainty bounds for the Mod-II configuration are generated, as shown in Fig. 17. This provides an estimation of the performance of this configuration in an environment similar to the original flight test data, accounting for the effects of uncertainty, noise, and wind.

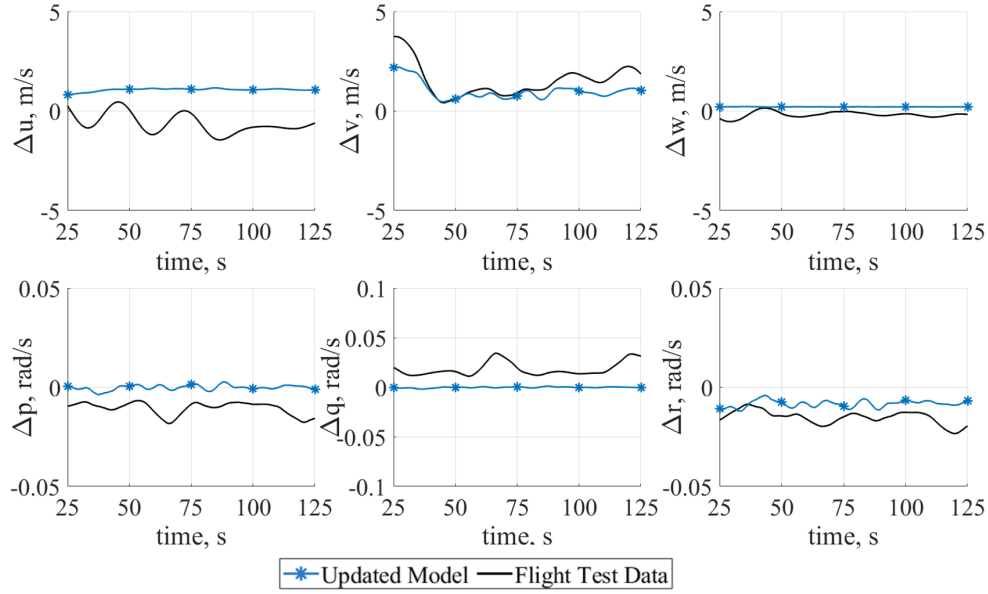


Fig. 14 Comparison of the Mod-I tuned model (blue) to Tecnam P2006T flight test data, showing agreement between the two.

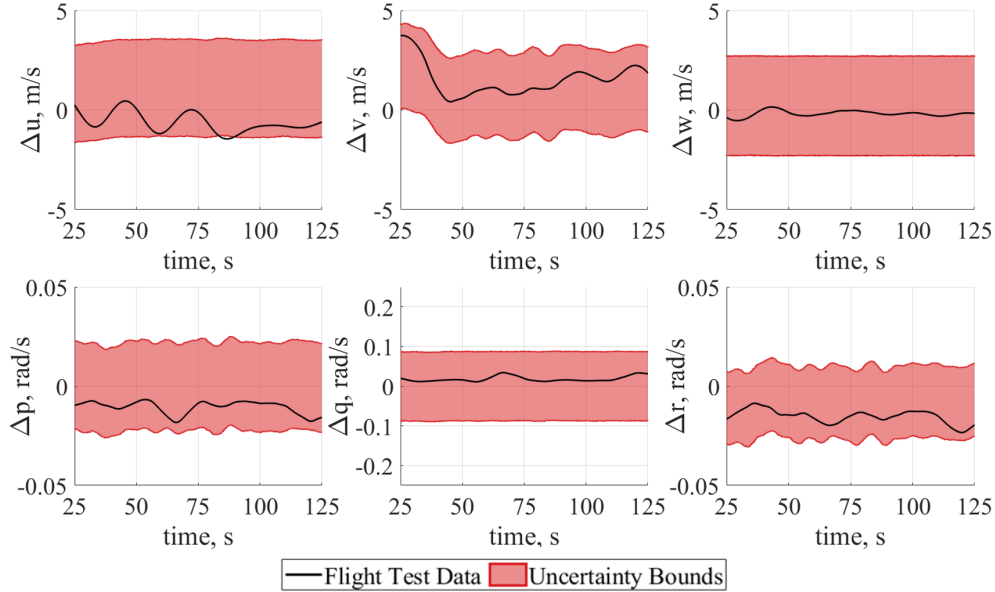


Fig. 15 Uncertainty bounds (red) from non-deterministic simulation for the X-57 Maxwell Mod-I configuration, containing almost all of the Tecnam P2006T flight test segment.

Figure 16 also shows a comparison between a simulation using the baseline model of the Mod-I configuration, in blue, to the baseline model of the Mod-III configuration, which has an updated wing and wing mounted engine nacelles, in purple. Although there are some minor differences between the two models, the difference, $\delta C_{*}^{base}|_{modIII}$ is still relatively small and the Tuned Model Method should be sufficient for predicting the performance and associated uncertainty. This estimate is shown in Fig. 18 and is remarkably similar to the predicted performance for the Mod-II configuration.

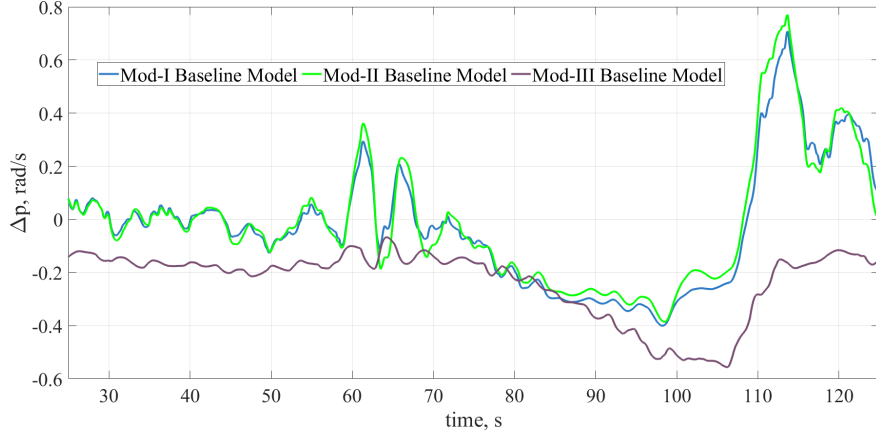


Fig. 16 Comparison of a simulation the baseline model for the Mod-I configuration (blue), the baseline model for the Mod-II configuration (green), and baseline model for the Mod-III configuration (black), demonstrating the differences between the three configurations.

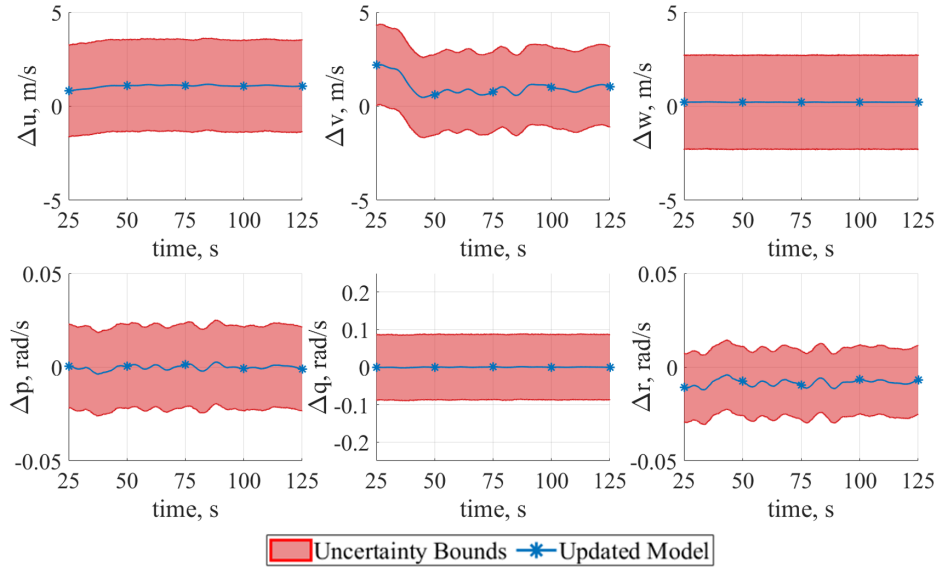


Fig. 17 Updated model, indicated by stars, and the associated uncertainty bounds, for the X-57 Maxwell Mod-II Configuration, illustrating the predicted performance.

The small difference between the estimated performance for the Mod-II and Mod-III configurations can be due to a number of factors. The large difference between the baseline model and the tuned model for the nominal Mod-I configuration is substantially larger than the differences seen between the configurations and therefore has a larger effect on the aircraft dynamics compared to the configuration changes. Improved baseline models, generated using a higher-order non-linear model form, could illustrate the effects of the modifications more clearly. A second potential cause for the similar estimated performance is the high process and sensor noise seen in the flight test data, due to the large uncertainty in the velocity, propulsion, and turbulent wind measurements. The inclusion of additional flight test data, which contain these signals, to the system identification process should create a tuned model that is able to more closely match the actual dynamics of the aircraft. Of course, this similarity could simply be due to the small changes between the configurations and an effort to design the modified configurations to have the same approximate performance as the original aircraft.

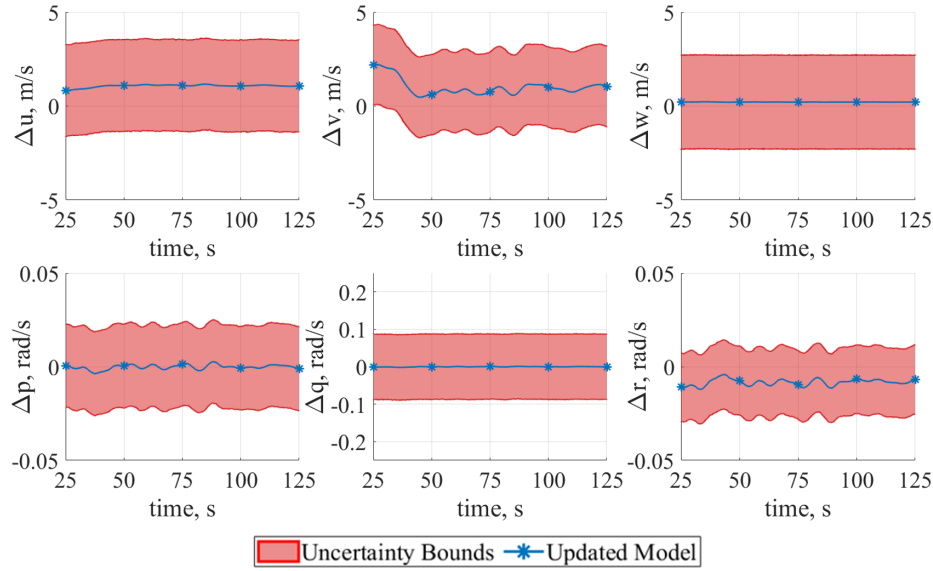


Fig. 18 Updated model, indicated by stars, and the associated uncertainty bounds, in red, for the X-57 Maxwell Mod-III configuration, illustrating the predicted performance. Note the similarity to the estimate for the Mod-II configuration.

G. Comparison to Airworthiness Certification Requirements

The framework results can also be used as a comparison to airworthiness certification requirements to serve as an additional resource prior to flight testing. Because the existing X-57 flight test data has high uncertainty in propulsive inputs, some critical certification requirements cannot be analyzed, including climb rates under 14 CFR Part 23.2120; however, other airworthiness and handling criteria can be evaluated [3].

One example handling criteria is the acceptable roll rate with maximum aileron deflection, which is typically under 10 degrees per second for normal category aircraft. Figure 19 shows the estimated response for a maneuver that includes full positive aileron deflection of 17 degrees at 5 seconds, a return to the neutral position, and then full negative aileron deflection of -17 degrees at 15 seconds, for the Mod-II configuration. The maximum roll rate achieved was just under ± 7 degrees per second, with minimal uncertainty, aligning with expected handling qualities for a normal category aircraft. The uncertainty bounds, shown in red in Fig. 19, are difficult to see due to the low uncertainty in this maneuver, which is expected due to the nature of the maneuver - a short, isolated control input with small deviation from aircraft trim. The results for the Mod-III configuration are similar.

VI. Summary and Conclusions

As the number of novel or modified aircraft designs continues to increase, predicting the performance of any modified configurations before flight test data are available can reduce both time and cost required. A previously defined framework is applied to NASA's X-57 Maxwell aircraft to estimate the performance of the various modifications, or "Mods." Predicted performance, including uncertainty bounds, were generated for the X-57 Mod-II and Mod-III configurations, which were similar for both modified configurations. These similarities could be due to the large difference between the baseline model and tuned model for the nominal Mod-I configuration, the large amount of signal and process noise in the flight test data used to generate the tuned model using system identification, or the specific design of the aircraft modifications. To improve the results, a higher-order non-linear model form and additional flight test data with supplemental sensors is recommended.

Because this aircraft has not yet flown, these predictions can be a useful comparison tool, by informing future flight testing, assessing models, and guiding any additional modifications. Future work includes comparing these results to the flight test data for the Mod-II and Mod-III configurations when they become available after flight testing is conducted.

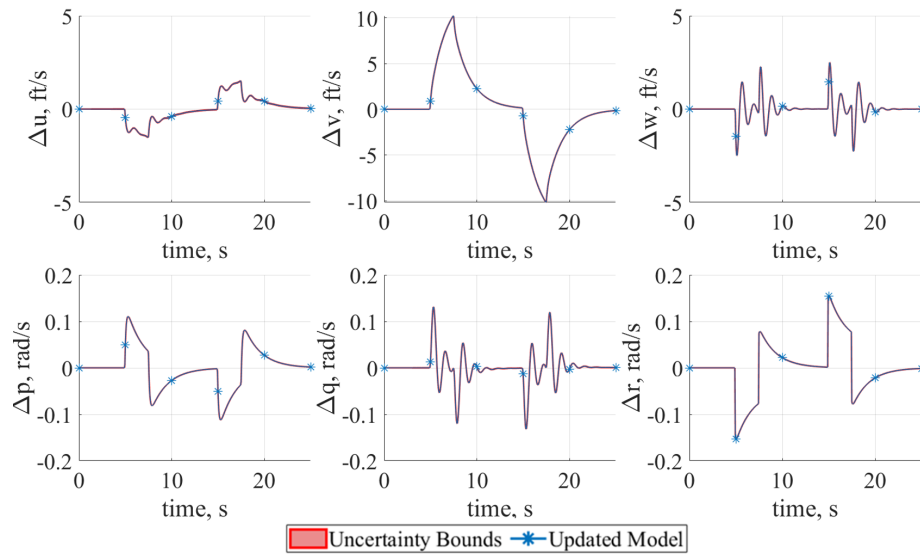


Fig. 19 Prediction of X-57 Mod-II response to full aileron inputs, with maximum positive aileron at 5 seconds and maximum negative aileron at 15 seconds, showing adequate handling qualities for a normal category aircraft.

Acknowledgments

This research was conducted as a part of NASA's Pathways Intern Employment Program in the Aeronautics Systems Analysis Branch at NASA Langley Research Center. This research was partially supported by NAVAIR under the Virginia Tech Airworthiness Center (VTAC) grant number N00421-16-2-B001. The authors would like to acknowledge technical input from Jessica Holmberg, John Leonard, Theresa Shafer, and Andrew Pontzer of NAVAIR. Additional input and assistance in obtaining the X-57 Maxwell simulations and flight test data was provided by Nick Borer (E403) and Dave Cox (D316) from NASA Langley.

References

- [1] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, 2010.
- [2] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commerical Derivative Aircraft Acquisitions," Master's thesis, University of Tennessee - Knoxville, Knoxville, TN, May 2003.
- [3] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2022. URL <https://www.ecfr.gov/>.
- [4] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Bevirt, J., Stoll, A. M., and Gibson, A. R., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," *16th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA 2016-3920, American Institute of Aeronautics and Astronautics, Washington, D.C., June 2016. doi:10.2514/6.2016-3920.
- [5] *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, 12700 Sunrise Valley Drive, Suite 200 Reston, VA 20191-5807, January 2021. doi:10.2514/4.106231.001.
- [6] Schaefer, J. A., Romero, V. J., Schafer, S. R., Leyde, B., and Denham, C. L., "Approaches for Quantifying Uncertainties in Computational Modeling for Aerospace Applications," *AIAA Scitech 2020 Forum*, AIAA 2020-1520, American Institute of Aeronautics and Astronautics, Orlando, FL, January 2020. doi:10.2514/6.2020-1520.
- [7] *Evaluation of Quantification of Margins and Uncertainties Methodology for Assessing and Certifying the Reliability of the Nuclear Stockpile*, National Academies Press, Washington, D.C., March 2009. doi:10.17226/12531.

- [8] Roy, C. J., and Balch, M. S., "A Holistic Approach to Uncertainty Quantification with Application to Supersonic Nozzle Thrust," *International Journal for Uncertainty Quantification*, Vol. 2, No. 4, 2012, pp. 363–381. doi:10.1615/Int.J.UncertaintyQuantification.2012003562.
- [9] Oberkampf, W., Helton, J., and Sentz, K., "Mathematical Representation of Uncertainty," *19th AIAA Applied Aerodynamics Conference*, AIAA 2001-1645, American Institute of Aeronautics and Astronautics, Anaheim, CA, June 2001. doi:10.2514/6.2001-1645.
- [10] Roy, C. J., and Oberkampf, W. L., "A Comprehensive Framework for Verification, Validation, and Uncertainty Quantification in Scientific Computing," *Computer Methods in Applied Mechanics and Engineering*, Vol. 200, No. 25, June 2011, pp. 2131–2144. doi:10.1016/j.cma.2011.03.016.
- [11] Denham, C. L., Patil, M., and Roy, C. J., "Estimating Uncertainty Bounds for Modified Configurations from an Aerodynamic Model of a Nominal Configuration," *2018 AIAA Atmospheric Flight Mechanics Conference*, AIAA 2018-1762, American Institute of Aeronautics and Astronautics, Kissimmee, FL, January 2018. doi:10.2514/6.2018-1762.
- [12] Denham, C. L., Patil, M., Roy, C. J., and Alexandrov, N., "Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations," *Aerospace*, Vol. 9, No. 9, Sep 2022, p. 490. doi:10.3390/aerospace9090490.
- [13] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Rules and Standards Review," NASA/CR-2019-220406, September 2019.
- [14] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Coordination Roadmap," NASA/CR-2019-220408, September 2019.
- [15] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Gap Analysis," NASA/CR-2019-220407, September 2019.
- [16] Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2nd ed., No. 245 in Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, Reston, VA, Jun 2015.
- [17] Hale, L. E., Patil, M., and Roy, C. J., "Nondeterministic Simulation for Probability of Loss of Control Prediction for Unmanned Aircraft Systems," *AIAA Modeling and Simulation Technologies Conference*, AIAA 2015-2329, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2015. doi:10.2514/6.2015-2329.
- [18] Montgomery, D. C., *Design and Analysis of Experiments*, eighth ed., John Wiley & Sons, Inc, Hoboken, NJ, 2013.
- [19] Yoo, S., and Duensing, J., "Computational Analysis of the External Aerodynamics of the Unpowered X-57 Mod-III Aircraft," *AIAA Aviation 2019 Forum*, AIAA 2019-3698, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2019. doi:10.2514/6.2019-3698.
- [20] Duensing, J. C., Yoo, S., Maldonado, D., Housman, J. A., Jensen, J. C., and Kiris, C. C., "Establishing Best Practices for X-57 Maxwell CFD Database Generation," *AIAA Scitech 2019 Forum*, AIAA 2019-0274, American Institute of Aeronautics and Astronautics, San Diego, CA, January 2019. doi:10.2514/6.2019-0274.
- [21] Borer, N. K., Cox, D. E., and Wallace, R. D., "Flight Performance Maneuver Planning for NASA's X-57 "Maxwell" Flight Demonstrator - Part 1: Power-Off Glides," *AIAA Aviation 2019 Forum*, AIAA 2019-2855, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2019. doi:10.2514/6.2019-2855.