Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations

Casey L. Denham

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Aerospace Engineering

Mayuresh Patil, Co-chair
Christopher J. Roy, Co-chair
Natalia Alexandrov
Mazen Farhood
Craig A. Woolsey

May 9th, 2022
Blacksburg, Virginia

Keywords: Uncertainty Quantification, Flight Dynamics, Modeling and Simulation

Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations

Casey L. Denham

(ABSTRACT)

Flight testing has been the historical standard for determining aircraft airworthiness - however, increases in the cost of flight testing and the accuracy of inexpensive CFD promote certification by analysis to reduce or replace flight testing. A framework is introduced to predict the performance in the special case of a modification to an existing, previously certified aircraft. This framework uses a combination of existing flight test or high fidelity data of the original aircraft as well as lower fidelity data of the original and modified configurations. Two methods are presented which estimate the model form uncertainty of the modified configuration, which is then used to conduct non-deterministic simulations. The framework is applied to an example aircraft system with simulated flight test data to demonstrate the ability to predict the performance and associated uncertainty of modified aircraft configurations. However, it is important that the models and methods used are applicable and accurate throughout the intended use domain. The factors and limitations of the framework are explored to determine the range of applicability of the framework. The effects of these factors on the performance and uncertainty results are demonstrated using the example aircraft system. The framework is then applied to NASA's X-57 Maxwell and each of its modifications. The estimated performance and associated uncertainties are then compared to the airworthiness criteria to evaluate the potential of the framework as a component to the certification by analysis process.

Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations

Casey L. Denham

(GENERAL AUDIENCE ABSTRACT)

Aircraft are required to undergo an airworthiness certification process to demonstrate the capability for safe and controlled flight. This has historically been satisfied by flight testing, but there is a desire to use computational analysis and simulations to reduce the cost and time required. For aircraft which are based on an aircraft which has already been certified, but contain minor changes, computational tools have the potential to provide a large benefit. This research proposes a framework to estimate the flight performance of these modified aircraft using inexpensive computational or ground based methods and without requiring expensive flight testing. The framework is then evaluated to ensure that it provides accurate results and is suitable for use as a supplement to the airworthiness certification process.

Dedication

This work is dedicated to the memory of Dr. Paul A. Lagace MIT SB '78, SM '79, PhD '82. A mentor, father figure, advisor, teacher, supporter, MIT lifer, Boston sports fan, and most of all a friend. I wish you were here.

"A good teacher is like a candle - consuming itself to light the way for others"

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. Special thanks to Dr. Dave Cox of NASA Langley Research Center's Dynamic Systems Controls Branch for his assistance in updating the GTM Design Simulation, Dr. Eugene Morelli for his guidance with system identification, and the members of the Aeronautics Systems Analysis Branch for their support and guidance.

Thank you to my advisors and committee members for allowing me to continue my degree remotely while working at NASA. Thank you to all of my family for putting up with me for the past 7 years as I have struggled and succeeded. And of course, thank you to my taekwondo family from MIT, tBos, Virginia Tech, ACATA, and William & Mary, for always being there when I needed to kick something.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

The aircraft airworthiness certification process has traditionally relied on flight testing to determine whether the system meets the minimum standards of airworthiness, safety of flight, and risk [1]. Many organizations tasked with airworthiness certification, such as the the Federal Aviation Administration (FAA) and Naval Air Systems Command (NAVAIR), are required to consider modifications, such as an added radome, to a previously certified aircraft as an entirely separate aircraft for the purposes of certification [1, 2, 3]. Because these modifications are about the same aircraft, performing flight tests of many modifications is not time or cost efficient.

There is currently interest in certification by analysis or the use of analysis and simulation to supplement or replace flight testing in the certification process [4]. In particular, there is a desire to use analysis and simulation to estimate the performance, including associated uncertainty, of modifications to a previously certified aircraft [4, 5]. These modified configurations must still be accurately modeled and simulated with limited or no flight test data in order to meet the standards of airworthiness with the same level of confidence [5]. Certification by analysis is already commonly done in the nuclear industry, due to the high risks and costs associated with full-scale testing [6].

This research proposes a framework using uncertainty analysis and non-deterministic simulations to estimate the flight performance of modified aircraft configurations without requiring flight test data of the modified configuration. This estimated performance could then be used to reject unsuitable configurations or otherwise inform the flight test process.

1.2 Literature Review

Uncertainty quantification is of growing importance in the field of modeling and simulation, especially for aerospace applications [7, 8]. There are various types of uncertainty, including input uncertainty, numerical uncertainty, and model form uncertainty [9]. The present research focuses on model form uncertainty, which originates due to the structure of the selected model (for example, by neglecting higher order or non-linear terms) [7, 8]. This uncertainty can be placed into two categories. The first, epistemic uncertainty, is due to lack of knowledge and is represented by the range of possible values, without knowledge of the distribution [9, 10, 11]. Aleatory uncertainty is due to inherent randomness and is usually characterized probabilistically [9, 10, 11]. Quantifying and accounting for model form uncertainty is especially important when considering conditions where experimental data is limited or non-existent [6, 9, 10].

Uncertainty analysis can be an important aspect throughout all phases of aircraft simulation and modeling, including design, testing, and evaluation. Uncertainty quantification and analysis is frequently performed on Computational Fluid Dynamics (CFD) results at many stages of the code development and use [12]. Previously, uncertain terms have been used to perform deterministic simulations where the aerodynamic parameters are updated following the simulation, but are not varied during the simulation [13]. Uncertain wind gusts have been used in non-deterministic aerodynamics simulations with known aerodynamic parameters, especially looking at the effects on aircraft loading [14]. Simulations using aerodynamic uncertainty have also been used to aid in the design process by allowing for improvements to technology to be incorporated into the process and ensure that new designs are capable of meeting the same certification standards [15]. In order to provide improved control to systems with time-varying uncertain parameters, controllers have been created and refined using system data which account for uncertainty, but without calculating the parameter values and uncertainty directly [16]. Non-deterministic simulations have been used as subcomponents of more complex aircraft simulations, allowing for analysis of uncertainty within a given component, such as the fuel systems [17].

Full non-deterministic aircraft flight dynamics simulations have been previously used to evaluate the performance of an aircraft in a variety of conditions and when the aircraft dynamics are not known exactly [18, 19]. Prior work included using a baseline model of the aircraft dynamics, created using flight test data, which was then tuned using additional flight test data [18]. Probability Bounds Analysis (PBA) was used to calculate uncertainty bounds for the aircraft dynamics and non-deterministic simulations were then conducted [18]. PBA allows for the creation of uncertainty bounds for model form uncertainty by a comparison of the simulation and experimental data [19, 20]. The non-deterministic simulations allow for estimates of aircraft performance, given uncertainties in the aircraft dynamics, for a range of environments, allowing for probability of loss of control prediction [18]. The results can also be extended to other quantities of interest during the airworthiness certification process, such as maximum winds allowed, climb rate, and landing distance.

1.3 Problem Statement

Modifications to existing aircraft configurations can have a dearth of data compared to the existing aircraft, including data from wind tunnel tests, flight tests, and Computational Fluid Dynamics (CFD), depending on the development of the proposed modification. To provide additional resources for the flight certification process, non-deterministic simulations of modified aircraft configurations are proposed. Since there might not always be flight test data available for model tuning, uncertainty quantification, and non-deterministic simulations for these modified configurations, the framework uses knowledge of the unmodified, nominal configuration to assist in the simulation of the modified configuration. Two methods are proposed to estimate the modified aircraft dynamics and the uncertainties of the modified aircraft dynamics, using aspects of the nominal system, which can then be used to perform non-deterministic simulations. 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 framework can also be used prior to flight testing to provide an estimate of expected performance.

In the realm of verification and validation, there are three aspects to model validation: assessment of model accuracy, extrapolation of the model to the intended use, and model adequacy for the intended use [21]. These aspects can be extended to framework validation to ensure that a framework is suitable for its intended use. The proposed framework is evaluated against these benchmarks to determine the suitability of the framework as a component or precursor to certification by analysis.

1.4 Assumptions

This research relies heavily on the assumption that there is a limited amount of higher fidelity data available, which does not allow for suitable observation or calculation of the airworthiness characteristics. This higher fidelity data will generally be collected by flight testing, so it is assumed that sufficient data will exist for the previously existing nominal aircraft. The flight test data may range in quality from research-focused flight maneuvers designed to fully capture the aircraft dynamics to operational flight maneuvers. While the data quality may affect the accuracy or usefulness of the results, as discussed in 3, the framework can accept any range of quality.

The second major assumption of this research is that there is an ample amount of lower fidelity data available with which to make a model. This data is not necessarily low fidelity or low data quality in the typical sense, but rather the model it creates is lower fidelity than flight test data. An example of this would be a linear aircraft model generated from CFD data - even if the CFD data is of extremely high quality, a linear model will not include all higher order terms and effects seen in flight testing. While this data may be referred to as ”inexpensive” compared to flight test data, there may still be a significant cost and time associated with obtaining this data. Because this lower fidelity data is required for both the nominal and modified configurations, it is also assumed that the data quality between the two is roughly equal. For instance, if considering CFD data, the numerical, iterative, and discretization errors should be negligible and approximately equal between the two configurations.

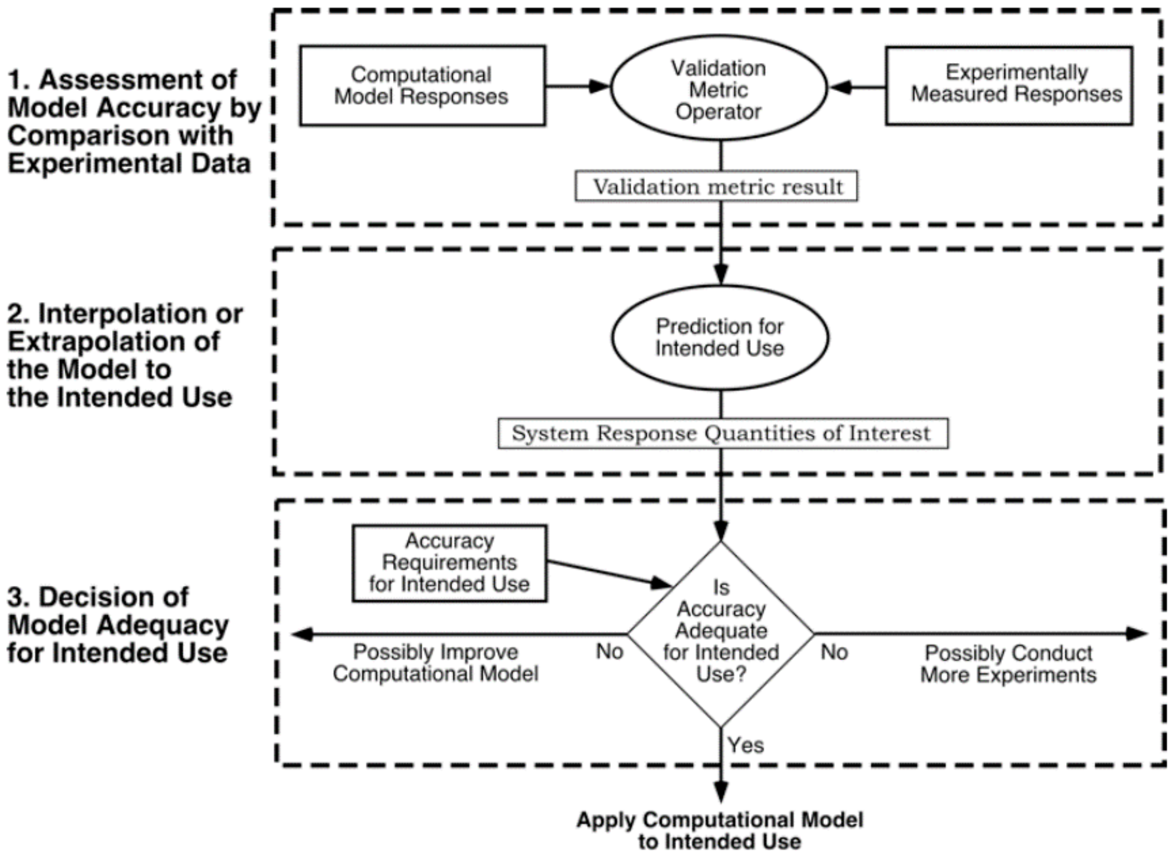

Figure 1.1: The three aspects of model validation [21]. Used with permission.

1.5 Contributions

Chapter 2 presents the proposed framework and performs an assessment of the model accuracy using the method of manufactured universes and an example aircraft system with simulated flight test data. A high fidelity simulation of this aircraft is used to create simulated flight test data as well as linearized models. First, the approach for calculating the initial models, as well as the uncertainty for the nominal system, is described. Next, the two methods of estimating the model and uncertainty for the modified configurations are introduced. These methods are then validated using the method of manufactured universes framework with simulated aircraft data [22].

Chapter 3 examines the applicability of the framework to its intended use. This chapter revisits the two methods of estimating the performance and associated uncertainty of modified aircraft configurations presented in Chapter 2 and explores the factors that affect the range of applicability of these methods, focusing on the effect of uncertainty estimation. Data from NASA Langley Research Center's Generic Transport Model aircraft is used to illustrate these limitations and the effect they have on the resulting non-deterministic simulation results.

Chapter 4 explores the adequacy of the framework to its intended use for certification by analysis of modified aircraft configurations. This chapter demonstrates the applicability of the framework using the real life example of the NASA X-57 Maxwell, an aircraft designed to demonstrate the benefits of distributed electric propulsion through a series of incremental modifications. The results produced by the framework are compared to the airworthiness certification criteria to demonstrate the potential of the framework for use in supplementing certification by analysis.

Bibliography

[1] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, March 2010.

[2] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commercial Derivative Aircraft Acquisitions," Masters thesis, Knoxville, TN, May 2003.

[3] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2021. URL https://www.ecfr.gov/.

[4] American Institute of Aeronautics and Astronautics (ed.), *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, January 2021. doi:10.2514/4.106231.001, URL https://arc.aiaa.org/doi/10.2514/4.106231.001.

[5] 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, URL https://arc.aiaa.org/doi/10.2514/6.2020-1520.

[6] *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, URL http://www.nap.edu/catalog/12531.

[7] Mehta, U. B., Eklund, D. R., Romero, V. J., Pearce, J. A., and Keim, N. S., "Simulation Credibilty - Advances in Vertification, Validation, and Uncertainty Quantification," NASA TP-2016-219422, November 2016.

[8] 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, URL https://linkinghub.elsevier.com/retrieve/pii/S0045782511001290.

[9] 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, URL http://www.dl.begellhouse.com/journals/52034eb04b657aea,43e225911b944538,340d23ed5c6d1633.html.

[10] 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, URL https://arc.aiaa.org/doi/10.2514/6.2001-1645.

[11] Oberkampf, W. L., DeLand, S. M., Rutherford, B. M., Diegert, K. V., and Alvin, K. F., "Error and Uncertainty in Modeling and Simulation," *Reliability Engineering & System Safety*, Vol. 75, No. 3, March 2002, pp. 333–357. doi:10.1016/S0951-8320(01)00120-X, URL https://linkinghub.elsevier.com/retrieve/pii/S095183200100120X.

[12] Schaefer, J. A., Cary, A. W., Duque, E. P., and Lawrence, S., "Application of a CFD Uncertainty Quantification Framework for Industrial-Scale Aerodynamic Analysis," *AIAA Scitech 2019 Forum*, AIAA 2019-1492, American Institute of Aeronautics and Astronautics, San Diego, CA, Janary 2019. doi:10.2514/6.2019-1492, URL https://arc.aiaa.org/doi/10.2514/6.2019-1492.

[13] Wendorff, A. D., Alonso, J. J., and Bieniawski, S. R., "A Multi-Fidelity Approach to Quantification of Uncertainty in Stability and Control Databases for use in Stochastic Aircraft Simulations," *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2015-3439, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2015. doi:10.2514/6.2015-3439, URL http://arc.aiaa.org/doi/10.2514/6.2015-3439.

[14] Fidkowski, K., Kroo, I., Willcox, K., and Engelson, F., "Stochastic Gust Analysis Techniques for Aircraft Conceptual Design," *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2008-5848, American Institute of Aeronautics and Astronautics, Victoria, British Columbia, Canada, September 2008. doi:10.2514/6.2008-5848, URL http://arc.aiaa.org/doi/10.2514/6.2008-5848.

[15] Ng, L. W. T., and Willcox, K. E., "Monte Carlo Information-Reuse Approach to Aircraft Conceptual Design Optimization Under Uncertainty," *Journal of Aircraft*, Vol. 53, No. 2, March 2016, pp. 427–438. doi:10.2514/1.C033352, URL http://arc.aiaa.org/doi/10.2514/1.C033352.

[16] Kramer, B., Peherstorfer, B., and Willcox, K., "Feedback Control for Systems with Uncertain Parameters Using Online-Adaptive Reduced Models," *SIAM Journal on Applied Dynamical Systems*, Vol. 16, No. 3, January 2017, pp. 1563–1586. doi: 10.1137/16M1088958, URL https://epubs.siam.org/doi/10.1137/16M1088958.

[17] Steinkellner, S., "Aircraft Vehicle Systems Modeling and Simulation under Uncertainty," Master's thesis, Linköping University Institute of Technology, Linköping, Sweden, 2011. URL http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-68068.

[18] 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, Dallas, TX, June 2015. doi: 10.2514/6.2015-2329, URL http://arc.aiaa.org/doi/10.2514/6.2015-2329.

[19] Hale, L. E., Patil, M., and Roy, C. J., "Aerodynamic Parameter Identification and Uncertainty Quantification for Small Unmanned Aircraft," *AIAA Guidance, Navigation, and Control Conference*, AIAA 2015-1538, American Institute of Aeronautics and Astronautics, Kissimmee, FL, January 2015. doi:10.2514/6.2015-1538, URL http://arc.aiaa.org/doi/10.2514/6.2015-1538.

[20] Maine, R. E., and Iliff, K. W., "The Theory and Practice of Estimating the Accuracy of Dynamic Flight-Determined Coefficients," NASA RP-1077, July 1981.

[21] Oberkampf, W. L., and Trucano, T. G., "Verification and Validation Benchmarks," SAND2007-0853, Albuquerque, NM, February 2007.

[22] Stripling, H., Adams, M., McClarren, R., and Mallick, B., "The Method of Manufactured Universes for Validating Uncertainty Quantification Methods," *Reliability Engineering & System Safety*, Vol. 96, No. 9, September 2011, pp. 1242–1256. doi: 10.1016/j.ress.2010.11.012, URL https://linkinghub.elsevier.com/retrieve/pii/S0951832011000755.

Chapter 2

Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations

Casey L. Denham
Mayuresh Patil
Christopher J. Roy
Natalia Alexandrov

Note: This chapter comes from a journal paper manuscript. The author performed the work and wrote the article under guidance from the co-authors.

Abstract

Flight testing has been the historical standard for determining aircraft airworthiness. However, increases in the cost of flight testing and the accuracy of inexpensive CFD encourage the adoption of certification by analysis to reduce or replace flight testing. A framework is introduced to predict the performance in the special case of a modification to an existing, previously certified aircraft. This framework uses a combination of existing flight test or high fidelity data of the original aircraft as well as lower fidelity data from CFD or wind tunnel testing of the original and modified configurations to create 6-DOF flight dynamics models. Two methods are presented which generate an updated flight dynamics model and estimate the model form uncertainty for the modified aircraft configuration. This updated dynamics model and uncertainty estimate is then used to conduct non-deterministic simulations with wind turbulence included. The framework is applied to an example aircraft system to demonstrate the ability to predict the performance and associated model form uncertainty of modified aircraft configurations.

2.1 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
δT	=	throttle deflection
δC_*^{base}	=	change in baseline model due to modified configuration, difference between modified configuration and nominal configuration
δC_*^{tun}	=	additional correction due to tuning of modified configuration model
$\delta C_*^{UQ}\|_{base}$	=	additional uncertainty bounds from model form uncertainty for modified configuration, evaluated about the baseline model
$\delta C_*^{UQ}\|_{tun}$	=	additional uncertainty bounds from model form uncertainty for modified configuration, evaluated about the tuned model
ΔC_*^{tun}	=	correction due to model tuning, difference between tuned model and baseline model for nominal configuration
$\Delta C_*^{UQ}\|_{base}$	=	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

2.2 Introduction

The aircraft airworthiness certification process has traditionally relied on flight testing to determine whether the system meets the minimum standards of airworthiness, safety of flight, and risk [1]. Organizations tasked with airworthiness certification, such as the the Federal Aviation Administration (FAA) and Naval Air Systems Command (NAVAIR), are required to consider modifications, such as an added radome, to a previously certified aircraft as an entirely separate aircraft for the purposes of certification [1, 2, 3]. Because these modifications are about a single reference aircraft, performing time-consuming and expensive flight tests may not be justified for some modifications.

There is currently interest in certification by analysis, or the use of analysis and simulation to supplement or replace flight testing in the certification process, in the aviation community - notably by the AIAA Certification by Analysis (CbA) Community of Interest (CoI), which released a set of recommended practices in 2021 [4]. In particular, there is a desire to use analysis and simulation to model modifications to a previously certified aircraft and associated uncertainties [5]. These modified configurations must still be accurately modeled and simulated with limited or no flight test data in order to meet the standards of airworthiness with the same level of confidence [5]. Certification by analysis is already commonly done in the nuclear industry, due to the high risks and costs associated with testing [6]. This paper proposes a framework using uncertainty analysis and non-deterministic simulations to estimate the flight performance of modified aircraft configurations without requiring flight test data of the modified configuration. In the future and with additional development, this estimated performance could then be used to reject unsuitable configurations or otherwise inform the flight test process.

Uncertainty quantification is of growing importance in the field of modeling and simulation, especially for aerospace applications [7, 8]. There are various types of uncertainty, including input uncertainty, numerical uncertainty, and model form uncertainty [9]. The present research focuses on model form uncertainty, which originates due to the structure of the selected model (for example, by neglecting higher order or non-linear terms) [7, 8]. Uncertainty, including model form uncertainty, can be placed into two categories. The first, epistemic uncertainty is due to lack of knowledge and represented by the range of possible values, without knowledge of the distribution [9, 10, 11]. Aleatory uncertainty is due to inherent randomness and is usually characterized probabilistically [9, 10, 11]. Quantifying and accounting for model form uncertainty is especially important when considering conditions where experimental data are limited or non-existent [6, 9, 10].

Uncertainty analysis can be an important aspect throughout all phases of aircraft simulation and modeling, including design, testing, and evaluation. Uncertainty quantification and analysis is frequently performed on Computational Fluid Dynamics (CFD) results at many stages of the code development and use [12]. Previously, uncertain terms have been used to perform deterministic simulations where the aerodynamic parameters are updated following the simulation, but are not varied during the simulation [13]. Uncertain wind gusts have been used in non-deterministic aerodynamics simulations with known aerodynamic parameters, especially looking at the effects on aircraft loading [14]. Simulations using aerodynamic uncertainty have also been used to aid in the design process by allowing for improvements to technology to be incorporated into the process and ensure that new designs are capable of meeting the same certification standards [15]. Non-deterministic simulations have been used as sub-components of more complex aircraft simulations, allowing for analysis of uncertainty within a given component, such as the fuel systems [16].

Full non-deterministic aircraft flight dynamics simulations have been previously used to evaluate the performance of an aircraft in a variety of conditions and when the aircraft dynamics are not known exactly [17, 18]. Prior work included using a baseline model of the aircraft dynamics, created using flight test data, which was then tuned using additional flight test data [17]. Probability Bounds Analysis (PBA) was used to calculate uncertainty bounds for the aircraft dynamics and non-deterministic simulations were then conducted [17]. PBA allows for the creation of uncertainty bounds for model form uncertainty by a comparison of the simulation and experimental data [18, 19]. The non-deterministic simulations allow for estimates of aircraft performance, given uncertainties in the aircraft dynamics, for a range of environments, allowing for probability of loss of control prediction [17]. The results can also be extended to other quantities of interest during the airworthiness certification process, such as maximum winds allowed, climb rate, and landing distance.

Modifications to existing aircraft configurations can have a dearth of data compared to the existing aircraft, including data from wind tunnel tests, flight tests, and Computational Fluid Dynamics (CFD), depending on the development of the proposed modification. To provide additional resources for the flight certification process, non-deterministic simulations of modified aircraft configurations are proposed. Since there might not always be flight test data available for model tuning, uncertainty quantification, and non-deterministic simulations for these modified configurations, the proposed process uses knowledge of the unmodified, nominal configuration to assist in the simulation of the modified configuration. Two methods are proposed to estimate the modified aircraft dynamics and the uncertainties of the modified aircraft dynamics, using aspects of the nominal system, which can then be used to perform non-deterministic simulations. This framework is designed 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 framework can also be used prior to flight testing to provide an estimate of expected performance.

First, the approach for calculating the initial models, as well as the uncertainty for the nominal system, is described. Next, the two methods of estimating the model and uncertainty for the modified configurations are introduced. These methods are then validated using simulated aircraft data, using the method of manufactured universes framework, which takes advantage of simulated data when typical validation data are unavailable [20]. The paper concludes with observations of the proposed framework and areas of future research.

2.3 Analysis of Nominal Configuration

One of the goals of this research is to estimate the flight performance and associated uncertainty of a modified aircraft configuration, without requiring flight test data for the modified configuration. For the purposes of this research, a modified configuration is a configuration that differs from the nominal configuration by one or more modifications, such as payload pods, increase in mass, or change in wing characteristics. For most aircraft with multiple configurations, there is often a configuration which is considered "nominal" and is the basis for any modifications. Although the nominal configuration will likely have flight test data or other higher fidelity data, the modified configurations may only have limited data available, typically from CFD or wind tunnel tests.

2.3.1 Generation of Baseline Models

The first model that is generated for the nominal configuration is the baseline model, which serves as a common denominator for corrections and modifications. This model should ideally be developed using a data collection method which is available for the nominal configuration as well as any modified configurations. For instance, CFD data is available for the nominal configuration and many modified configurations for the AeroStar aircraft used as a research testbed by NAVAIR, but flight test data are not available for all configurations. For the nominal configuration, an example aerodynamic coefficient for this model is indicated by C_*^{base}. Similarly, a baseline model for the modified configuration is also created, $C_*^{base}+\delta C_*^{base}$.

2.3.2 Generation of Tuned Model

The next model generated for the nominal configuration is the tuned model, which utilizes the most accurate data available, generally flight test data. While these data are more accurate, they may not exist for all configurations, so a tuned model can 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 it is not required to. The difference between the tuned model of the nominal configuration and the baseline model of the same configuration is represented by ΔC_*^{tun}. An improved model of the nominal configuration is then represented by $C_*^{nom} = C_*^{base} + \Delta C_*^{tun}$.

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 used to generate the model include equation error method, output error method, and filter error method, which are described in Ref [21].

2.3.3 Estimation of Model Form Uncertainty

The uncertainty of greatest interest for this research is model form uncertainty, or uncertainty due to the difference between the model and the true system. However, the limited availability, poor quality, or inherent noise of these data sources can contribute to additional uncertainty associated with the model.

To calculate this uncertainty, the model is evaluated at each time step of the flight test data and is then compared to the values from the original data. This generates a series of time-independent errors for each timestep, as shown in Fig. 2.1 with blue dots for each timestep. Uncertainty bounds are estimated using 95% confidence intervals on the mean error between the higher fidelity data and the baseline or tuned model for each equation of motion as (2.1) [17, 22].

$$\hat{y}(x_o) - t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \leq \mu_{y|x0} \leq \hat{y}(x_o) + t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \qquad (2.1)$$

$\hat{y}(x_0)$ is the model response about the aircraft state x_0, $t_{\alpha/2,n-p}$ is the Student's t-distribution for 100(1-α) 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, $\mu_{y|x0}$ is the mean error of the model response at the aircraft state, and X is the matrix of observed data. These bounds are shown in Fig. 2.1 as red lines; note that the bounds used in non-deterministic simulations are modified from those calculated 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 increased bounds where data are sparse, as in Ref. [17]. Because the bounds grow exponentially as they move away from the available data, prediction for aircraft states far from observed values can lead to high uncertainty, as expected.

This uncertainty can be calculated about both the baseline and tuned models, creating two different uncertainty bounds, as shown in Figs. 2.2 and 2.3. When adding the uncertainty to our model of the nominal configuration, C_*^{nom}, two equations emerge, dependent on whether the tuning correction is used:

$$C_*^{nom} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} \qquad (2.2)$$

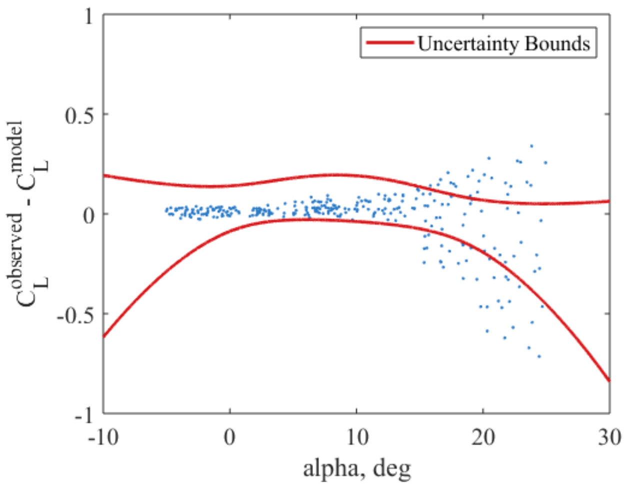

Figure 2.1: Calculation of uncertainty bounds, red, using differences between model and observed data, blue.

and

$$C_*^{nom} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} \tag{2.3}$$

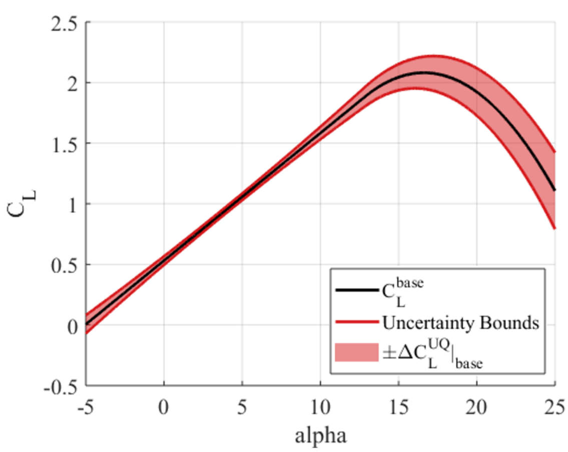

Figure 2.2: Uncertainty calculated about the baseline model.

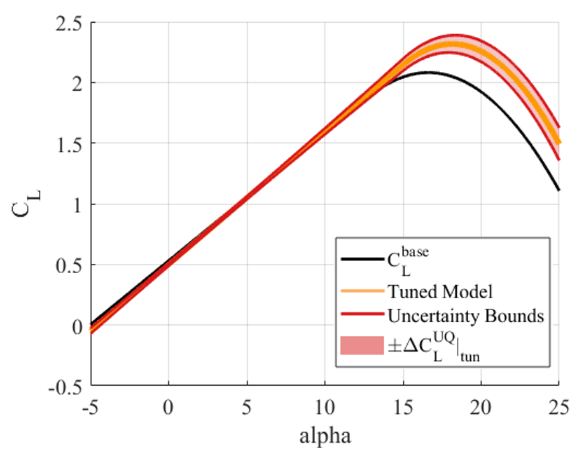

Figure 2.3: Uncertainty calculated about the tuned model. Note that the uncertainty is smaller because the tuned model is closer to the observed data.

2.3.4 Extension to Modified Aircraft Configurations

In order to perform non-deterministic simulations of modified aircraft configurations, an estimate of the model form uncertainty must first be obtained. Section 2.4 discusses the two methods to estimate this uncertainty based on the models of the nominal and modified configurations and flight test data for the nominal configuration.

2.3.5 Non-Deterministic Simulation

Non-deterministic simulations are conducted using the baseline and tuned models while accounting for changes due to modifications as well as uncertainty. Using the previously calculated uncertainty bounds, uncertainty in the states is added at each time step, dependent on the current state and control inputs. The simulation also includes a turbulent wind component, which adds additional realistic uncertainty to the simulation and better matches the simulated flight test data. To fully capture the 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 the number of simulation runs to achieve suitable convergence.

2.4 Analysis of Modified Configurations

A flight dynamics model for a modified configuration can be obtained from CFD or wind tunnel test data, but accounting for the difference between the model and flight test data for the nominal configuration, known as the tuning correction, allows for a better estimate of the true flight performance. The model form uncertainty of the modified configuration cannot be calculated without flight test data, but this uncertainty is valuable as a method to bound the predicted performance and capture the effects that cannot be easily obtained by ground based testing. Since there is no direct way to calculate the model form uncertainty for the modified configuration, it must be estimated.

This framework addresses the desire to accurately predict and bound the performance of modified aircraft configurations by utilizing knowledge of the nominal, unmodified configuration. Figure 2.4 illustrates the major stages of the framework. First, baseline models of the nominal configuration and any modified configurations are generated using lower fidelity data, such as CFD. Second, a tuned model of the nominal configuration is generated using system identification of available flight test data. Using these models and the flight test data, model form uncertainty is then estimated. Before proceeding, the models and uncertainty are validated to confirm that the models are adequate for their intended use [23]. Next, one of two methods described in Sections 2.4.1 and 2.4.2 are used to extend the aerodynamic model and uncertainty estimation to the modified configurations. Finally, non-deterministic flight dynamics simulations which account for uncertainty as well as wind turbulence are conducted in order to predict the performance and associated uncertainty bounds of the modified configurations.

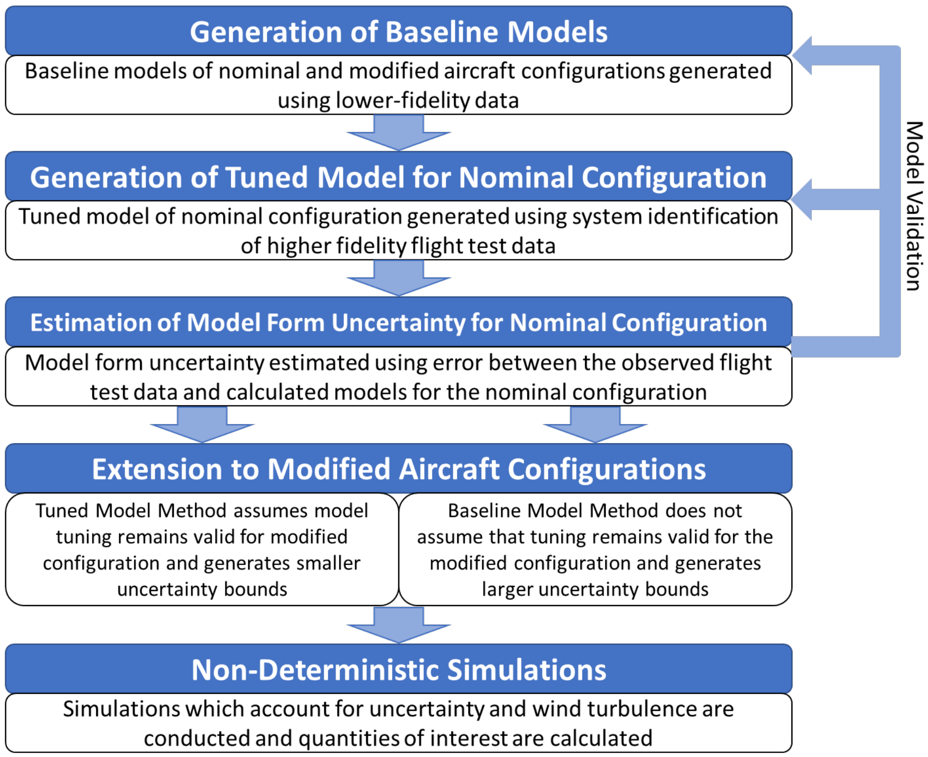

Figure 2.4: Illustration of the developed framework, showing the five main stages.

The first step in modeling a modified configuration is modeling the nominal, unmodified configuration, described in Section 2.3. The framework will be illustrated using a single model term but can be applied to all terms in the aircraft dynamics model. The nominal configuration of this aircraft can be described using a combination of the baseline model C_*^{base}, model tuning ΔC_*^{tun}, and uncertainty ΔC_*^{UQ}. Since we can calculate the model form error, which leads to the model form uncertainty, of the nominal configuration about both the baseline and tuned model, there are two related models, described above in Eqs. 2.2 and 2.3.

Equation (2.2) describes the case where the uncertainty is calculated about the baseline model, $C_*^{UQ}|_{base}$, whereas Eq. (2.3) describes the case where the uncertainty is calculated about the tuned model, $C_*^{UQ}|_{tun}$. For the nominal configuration, which has both lower fidelity and higher fidelity data and is therefore able to be tuned, Eq. (2.3) is more accurate and should always be used, but both equations are given to aid in developing the two methods for modeling for the modified configuration.

When we describe a modified aircraft configuration using the same nomenclature, additional terms appear due to the change in configuration. After including additional model tuning to match flight test data and uncertainty quantification, the final model for the modified configuration can be written in two different ways, corresponding to Eqs. (2.2) and (2.3):

$$C_*^{mod} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \pm \delta C_*^{UQ}|_{base} \tag{2.4}$$

$$C_*^{mod} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} + \delta C_*^{tun} \pm \delta C_*^{UQ}|_{tun} \tag{2.5}$$

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 (if available) for the modified configuration, and δC_*^{UQ} is the additional uncertainty for the modified configuration. Although δC_*^{base} can be obtained by comparing lower fidelity data of the nominal and modified configurations, such as wind tunnel or CFD data, δC_*^{tun} and δC_*^{UQ} cannot be calculated without higher fidelity data for the modified configuration, such as flight test data, which are often unavailable.

Using the prior knowledge of the nominal configuration, two methods are proposed to estimate the uncertainty of the modified configuration [24]. The methods differ in the approximation of δC_*^{tun} and δC_*^{UQ} and do not require parameter tuning and uncertainty quantification for the modified configuration. The methods are intended for small and large modifications, respectively, although the applicability of each method will be explored in future work.

2.4.1 Uncertainty Estimation Method 1 - Tuned Model Method

The first method to estimate the model and uncertainties of the modified configuration assumes that the total uncertainty for the modified configuration is equivalent to the uncertainty for the nominal configuration and that the model tuning for the nominal configuration also applies to the modified configuration. This is the same as assuming that no additional model tuning is needed for the modified configuration and the uncertainty bounds of the nominal configuration are valid for the modified configuration. This is a suitable assumption when the modification is small and has well-known and well-behaved aerodynamic effects. The determination of what constitutes a small modification is an area of future research.

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

$$C_* = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} \tag{2.6}$$

In other words, only the baseline model for the modified configuration is updated, i.e. corrected, using the change from the nominal configuration to the modified configuration

(δC_*^{base}), as shown in Fig. 2.5 using example artificial data. The uncertainty bounds for the nominal configuration ($\Delta C_*^{UQ}|_{tun}$), calculated using the tuned model, are then applied to this model to obtain updated uncertainty bounds for the modified configuration. This process is shown in Fig. 2.6 for the example data.

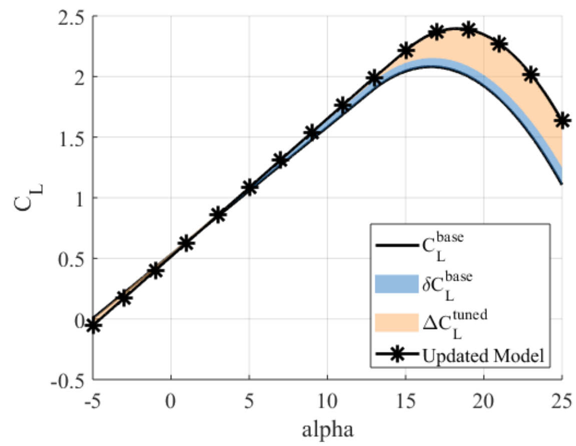

Figure 2.5: Generation of updated model for the modified configuration using the Tuned Model Method with example data. The changes due to the modification, in blue, and the tuning correction term, in yellow, are added to obtain the updated model

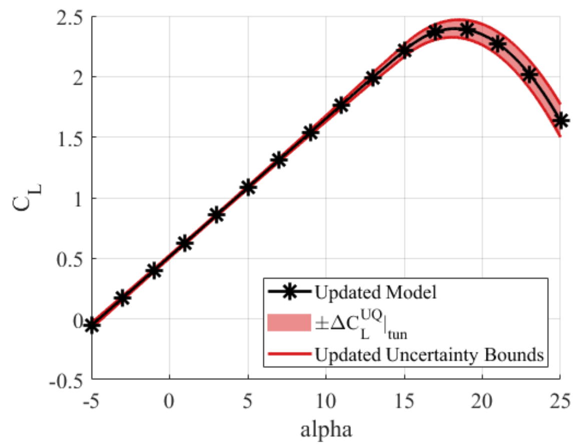

Figure 2.6: Addition of the uncertainty bounds, red, from the nominal configuration to the updated model of the modified configuration using the Tuned Model Method, showing the updated uncertainty bounds using example data.

2.4.2 Uncertainty Estimation Method 2 - Baseline Model Method

The second method of estimating the uncertainties of the modified configuration assumes that the total uncertainty for the modified configuration is the uncertainty that would occur if there were no tuning for the nominal configuration. This is equivalent to assuming the model tuning correction for the nominal configuration is no longer valid and approximating the total uncertainty for the modified configuration as the uncertainty for the nominal configuration with no tuning. Furthermore, it is assumed that the uncertainty bounds remain the same due to the similarity in configuration for the baseline modeling methods. The updated model for the modified configuration can then be written as

$$C_* = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \tag{2.7}$$

For this method, the baseline model for the nominal configuration has the change due to the modified configuration (δC_*^{base}) added to create the updated model, shown in Fig. 2.7 with the example data. Then, uncertainty bounds ($\Delta C_*^{UQ}|_{base}$) created using flight test data and the baseline model of the nominal configuration, as opposed to the tuned model used for the Tuned Model Method, are used. This creates much larger uncertainty bounds that include the effects of model tuning, as in Fig. 2.8.

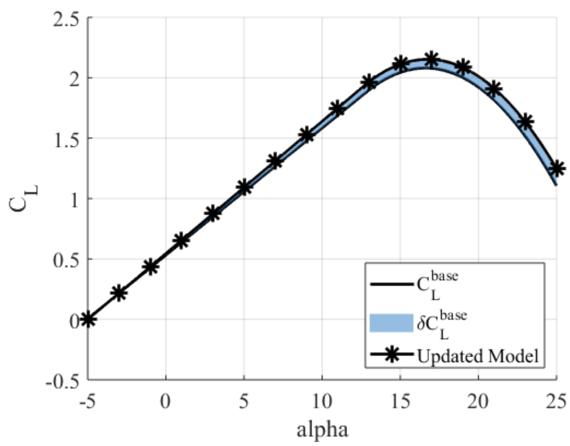

Figure 2.7: Generation of updated model for the modified configuration using the Baseline Model Method. The updated model for the modified configuration has only the changes due to the modification, in blue, added to the baseline model of the nominal configuration.

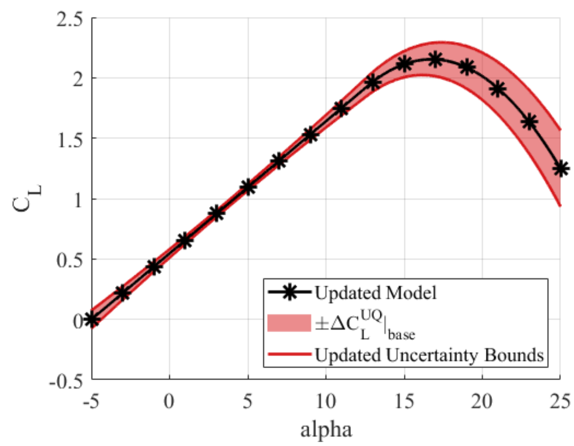

Figure 2.8: Calculation of the total uncertainty for the modified configuration using the Baseline Model Method, with example data. The total uncertainty is the uncertainty from the baseline model.

2.4.3 Use of the Two Methods

The two methods of estimating the uncertainty for modified configuration are expected to provide different levels of conservativeness, depending on the characteristics of the model and configuration. The Tuned Model Method, which assumes that the tuning is valid and leads to smaller uncertainty for the updated model, effectively tunes the model based on the nominal configuration. This assumption will lead to less conservative uncertainty bounds about the updated model. An updated model and corresponding uncertainties based on the Tuned Model Method are accurate for modified configurations that are similar to the nominal configuration - i.e. the modifications are minor. However, the Baseline Model Method, which assumed a larger uncertainty that includes the tuning of the baseline model, is expected to give more conservative bounds that will account for larger differences between the nominal and modified configurations. This is akin to saying that the tuning correction from the nominal configuration no longer applies to the modified configuration because the changes are sufficiently large. However, the precise definition of what constitutes a sufficiently large modification is still an area of active research.

2.5 Uncertainty Estimation for an Example Aircraft System

The framework is demonstrated using an example aircraft system through the method of manufactured universes, which allows for the validation of uncertainty quantification methods using simulated data and uncertainties [20]. Because high-fidelity or flight test data are not always available for modified aircraft configurations, this approach allows for direct comparison between predicted results and the "true" system response. It also enables the evaluation of the impact of noise level and data quality on the framework and results.

2.5.1 Example Aircraft System

NASA Langley Research Center's Generic Transport Model (GTM) aircraft, shown in Fig. 2.9, was chosen as the example aircraft system to demonstrate the proposed framework and methods. The GTM has had extensive wind tunnel, CFD, and flight tests and has been used for research including loss of control prediction, spin prediction, and control law development [25, 26, 27, 28]. An open-source high-fidelity, non-linear simulation of the GTM[1], created using a combination of wind tunnel, flight test, and simulation data was used for this research.

The aircraft simulation was tuned using a constant true airspeed, which results in the trimmed aircraft states in Table 2.1. Although the GTM simulation environment includes many control inputs, only throttle, elevator, rudder, and aileron deflections were used for this research, with all other surfaces kept at the trimmed or zero position. All simulation and uncertainty results are shown as deviations from the trimmed aircraft state and surface deflections.

The simulation includes a Dryden atmospheric turbulence model, allowing for the simulation of flight test data with process noise. Sensor noise was also included in the simulation, using the included noise model of the sensors present in the flight test vehicle. Separate simulated flight test data segments were created for system identification, uncertainty quantification, and uncertainty validation. Because this is simulated data, flight test data can also be created for the modified configurations.

2.5.2 Model Definitions for Example Aircraft System

A baseline model of the GTM was creating using the linearized longitudinal and lateral dynamics generated by the GTM simulation. This model serves as an approximation to CFD data and gives a lower fidelity aerodynamics model. A tuned model was created using the output error method to identify the system from simulated flight test data of independent

[1] Available at: https://github.com/nasa/GTM_DesignSim

Figure 2.9: NASA Langley's GTM aircraft during a flight test [25].

Table 2.1: GTM Trim States and Deflections

State	Trim Value
u	50.2 m/s
v	0 m/s
w	2.59 m/s
p	0 rad/s
q	0 rad/s
r	0 rad/s
ϕ	0 rad (0 deg)
θ	0.05 rad (2.86 deg)
Deflection	Trim Value
δ_e	2.45 deg
δ_r	0 deg
δ_a	-0.39 deg
δ_T	40.6%

elevator, rudder, and aileron doublets. A comparison of the baseline and tuned models to the observed flight test data is shown in Fig. 2.10. The tuned model is much closer to the simulated flight test data than the baseline model, capturing the aircraft dynamics more accurately.

Uncertainties were then calculated using the error between the artificial flight test data and the baseline and tuned models, shown in Figs. 2.11 and 2.12, respectively. As described in Section 2.3, these uncertainties can vary with aircraft state, but must always include the potential for no uncertainty. Because the uncertainty is calculated about different models, the differences are expected. Since the uncertainty is added to the derivatives of the states, even a small difference can have a large effect in the performance estimation. If the performance is to be estimated at a higher velocity or at a combination of angular rates, these states should be included in the data used for uncertainty quantification. If representative flight test data are not used in the calculation, the bounds will not adequately estimate the model form uncertainty. For this reason, the simulated flight test data used for uncertainty quantification included a combination of aircraft velocities, angular rates, and control deflections. Although these bounds are generated using 95% confidence intervals, some flight test data points appear to lie outside the bounds due to slicing the multi-dimensional space to be shown in a two-dimensional figure plane.

Three example modified configurations were also created. The first modification is a 10% increase in the aircraft mass, distributed equally, while the second modification is a 10% increase in the aircraft mass alongside a small change in aircraft center of gravity location, and the third modification is a 10% increase in aircraft mass alongside a larger change in aircraft center of gravity location. The first modification, with equally distributed mass, does

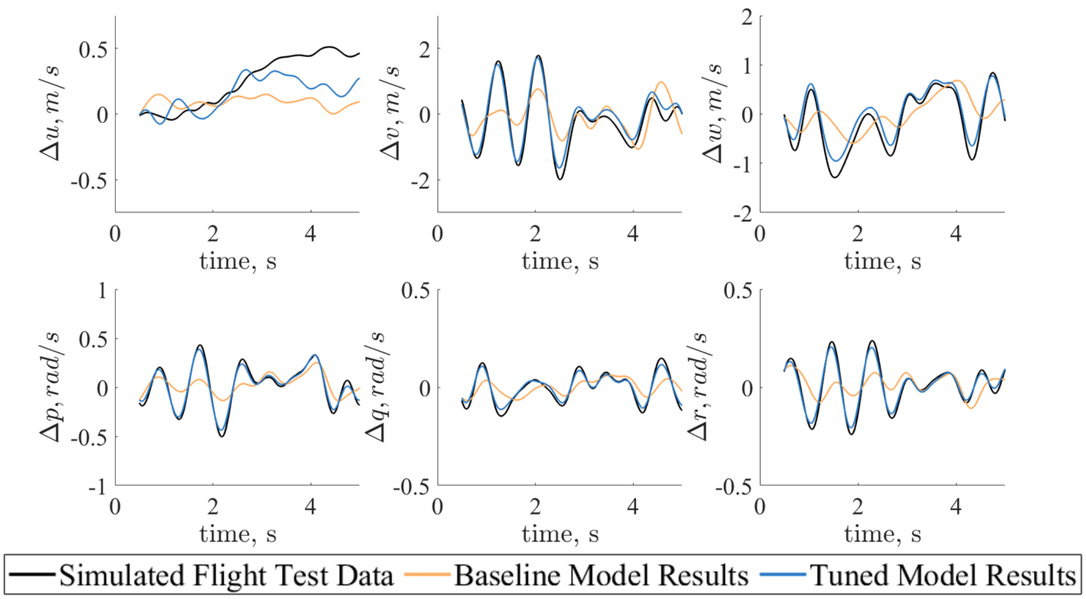

Figure 2.10: Comparison of the simulated flight test data, black, to the tuned model results, blue, and the baseline model results, orange.

not change the relationship between the moments of inertia and can therefore be modeled by the simple linear model. The second and third modifications, with a change to the center of gravity location, will cause changes to the moments of inertia that are not modeled. Although these modifications are not necessarily realistic, they serve to illustrate the methods and frameworks with both modeled and un-modeled modifications.

2.5.3 Uncertainty Estimation Methods for Example Aircraft System

The uncertainty estimation methods described in Section 2.3 were evaluated using the models and simulated flight test data for the modified GTM aircraft configurations. To do so, thousands of non-deterministic simulations were conducted, which include the estimated uncertainty evaluated at each timestep as a function of the aircraft state. The performance bounds are then calculated by taking the 95% bounds of these compiled simulations. Figure 2.13 shows the resulting updated model and associated uncertainty bounds for the Tuned Model Method, while Fig. 2.14 shows the results for the Baseline Model Method evaluated for the equally distributed mass modification. Due to the calculation in the updated model for each method, there are slight differences in the results for the updated model without the uncertainty. The Baseline Model Method also generates larger uncertainty bounds, most notably in the downward velocity (Δw) and yaw rate (Δr). The uncertainty in the forward velocity (Δu) is large in both methods, due to the large effects of the ignored non-linear

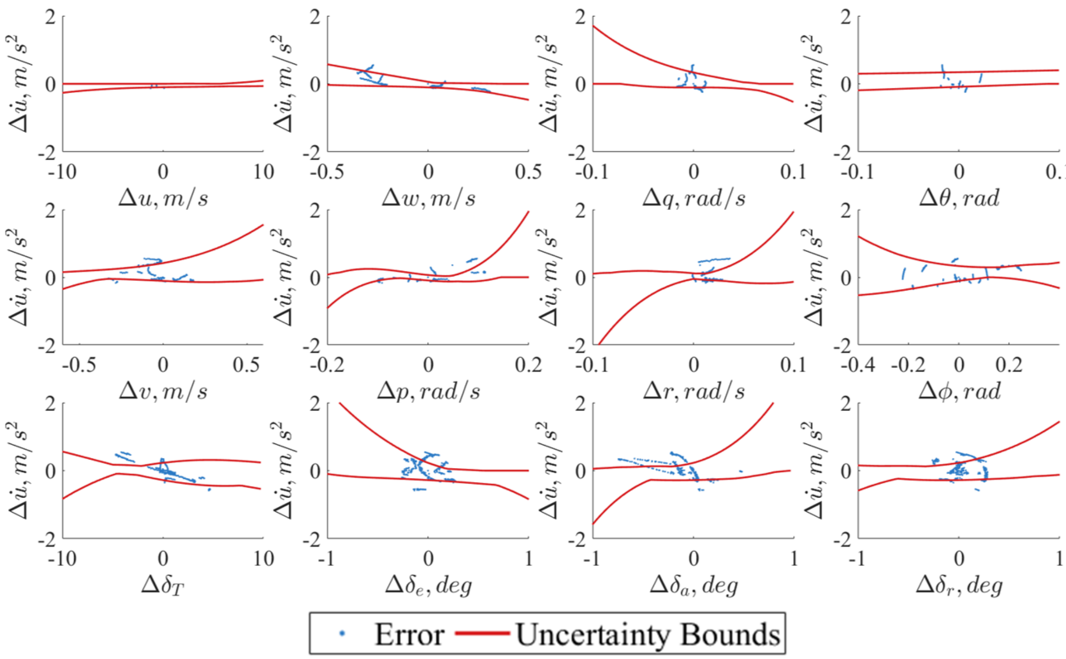

Figure 2.11: Calculation of the uncertainties for the baseline model. Errors between the observed data and the model results are shown in blue for each state, with the red lines indicating the 95% uncertainty bounds for $\Delta \dot{u}$.

dynamics.

2.6 Validation of Framework for an Example Aircraft System

2.6.1 Validation of Performance Estimation without Noise

Before validating the performance of the framework for a realistic case with both wind and signal noise, the no noise, no wind case was studied. Because these noise sources are included in the estimation of model form uncertainty, the no noise case allows evaluation of the framework with the most accurate estimation of uncertainty.

The tuned model for the nominal, unmodified configuration, closely matches the simulated flight test performance, shown in Fig. 2.15. For most of the aircraft states, the updated model correctly predicts the flight test performance, with the exception of the forward velocity, Δu. Forward velocity often has larger deviations in simulation and modeling due to non-linear terms that are excluded.

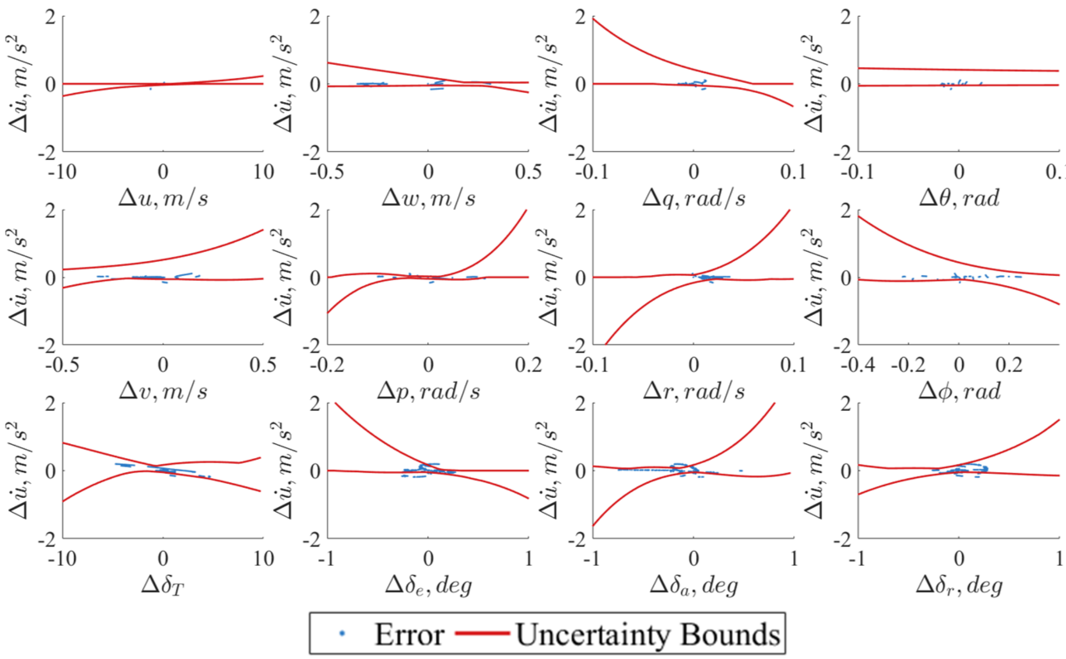

Figure 2.12: Calculation of the uncertainties for the tuned model. Errors between the observed data and the model results are shown in blue for each state, with the red lines indicating the 95% uncertainty bounds for $\Delta\dot{u}$.

When the Tuned Model Method is extended to a modified configuration, in this case the 10% increase in mass, the results remain in good agreement with the simulated flight test data. Figure 2.16 shows the comparison of the two, with the updated model generated using the Tuned Model Method in blue. There are distinct differences between the two, notably that the updated model has increased damping relative to the simulated flight test data and does not have the same peak magnitude in the velocity perturbations.

2.6.2 Validation of Performance Estimation

The uncertainty bounds generated from the Tuned Model Method and Baseline Model Method were then compared to the simulated flight test data for the three different modifications, using a separate validation maneuver. To evaluate the performance of the framework, the percentage of simulated flight test data falling within the estimated uncertainty bounds is calculated by evaluating whether each time step falls within the bounds, for all states. This metric counts each state independently, so a a timestep which is outside the bounds for multiple states would each have a negative impact. For the first modification of an equally distributed increase in mass, the uncertainty bounds generated contain the simulated flight test data for 94% of the data points, as shown in Fig. 2.17. This provides evidence that

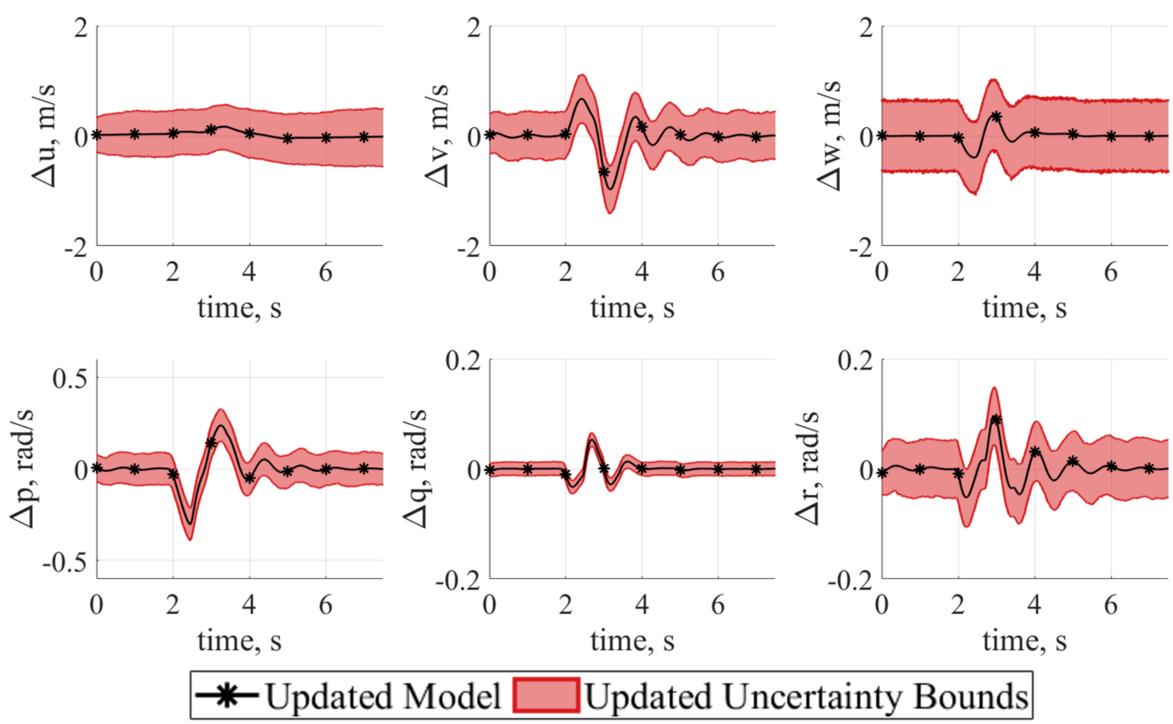

Figure 2.13: System response of updated aircraft model and associated uncertainties generated using the Tuned Model Method.

the method can correctly predict the performance of this configuration in a realistic scenario with both wind and sensor noise.

However, when these generated bounds are compared to the simulated flight test data for the second modification, of an unequally distributed mass with change in center of gravity location, the performance bounds only contain the simulated flight test data for 77% of the simulated flight test data points, shown in Fig. 2.18. The mismatch, most noticeable in downward velocity Δv and pitch rate Δq, is because the modification is not sufficiently represented by the lower fidelity models used to generate the uncertainty bounds, specifically the un-modeled change in moments of inertia. For these situations, the Baseline Model Method generates larger uncertainty bounds to capture more of the dynamics of the modified configurations. For the modification of the unequally distributed mass, the Baseline Model Method does capture more of the simulated flight test data, particularly the high angular rates, containing approximately 98% of the simulated flight test data points, as shown in Fig. 2.19. This significant increase is due to the larger estimated uncertainty bounds calculated with the Baseline Model Method, which is designed to be able to predict the performance of larger modifications.

As a further extension, these methods were applied to a modification with a 10% mass

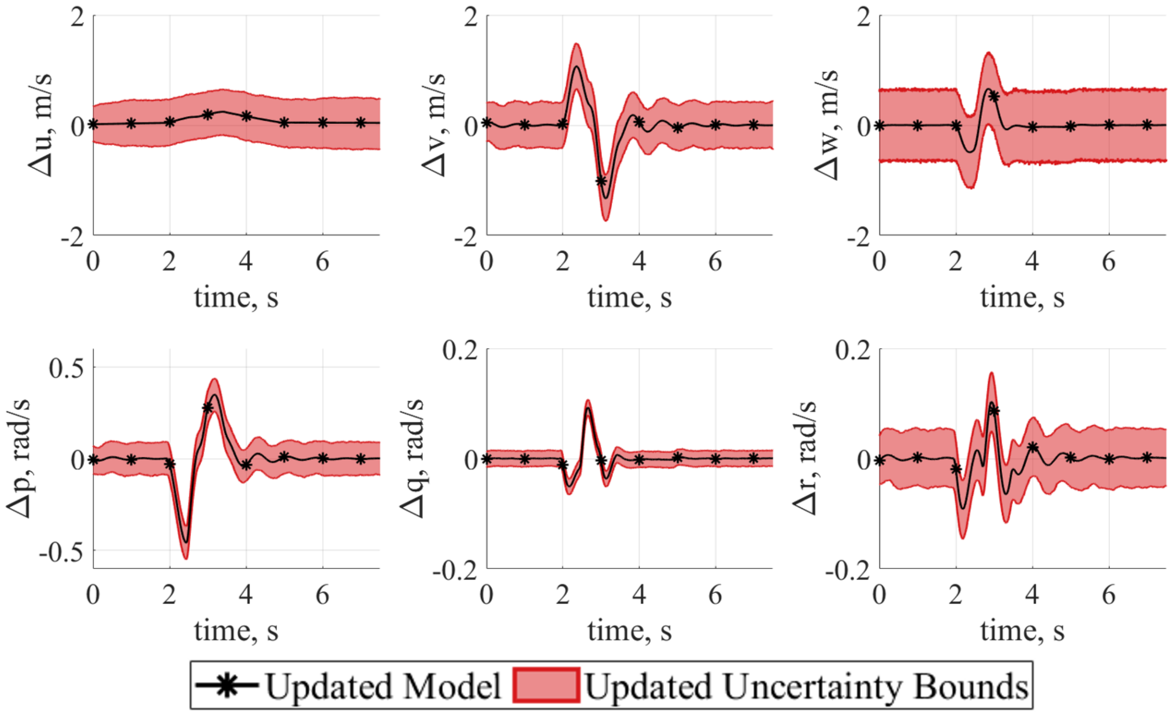

Figure 2.14: System response of updated aircraft model and associated uncertainties generated using the Baseline Model Method.

increase, but a much larger change in center of gravity location (Modification 3). When the Tuned Model Method was applied to this modification, the estimated performance bounds contained the simulated flight test data for only 19% of the data points, shown in Fig. 2.20. When the Baseline Model Method is applied to this configuration, the estimated performance bounds contain the simulated flight test data for 21% of the data points, a slight improvement but still significantly less than the previous configurations. The range of applicability of the uncertainty estimation methods is an area of active research.

Table 2.2 contains a summary of the results presented in this section, demonstrating the improvement in the amount of data points contained within the estimated performance bounds for the Baseline Model Method for the larger modifications and the small amount of data points contained when the two methods were used to estimate the performance of the configuration with a 10% mass increase with large change in center of gravity location.

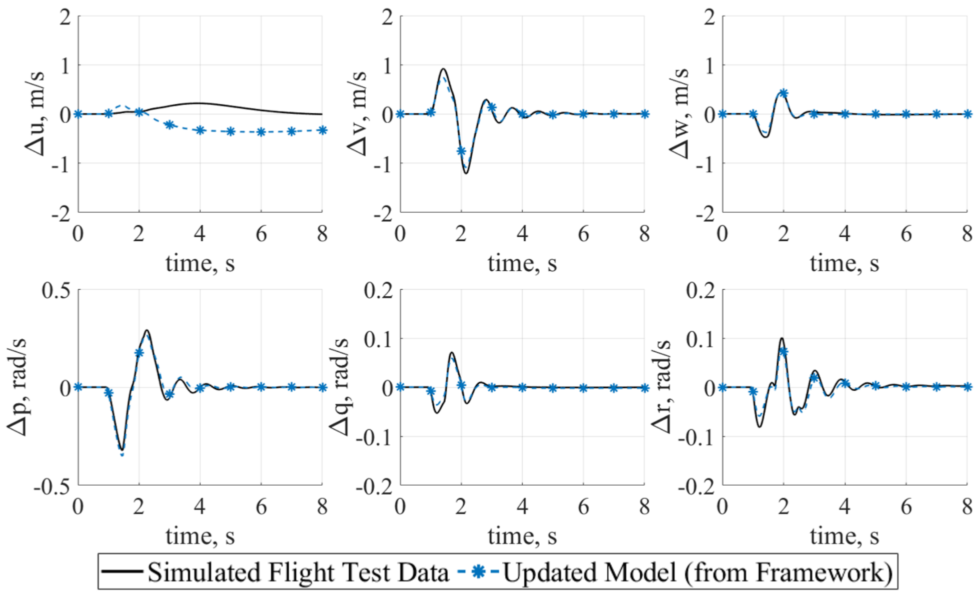

Figure 2.15: System response of updated aircraft model generated using the Tuned Model Method for the nominal configuration with no wind and no signal noise, showing a close match between the two.

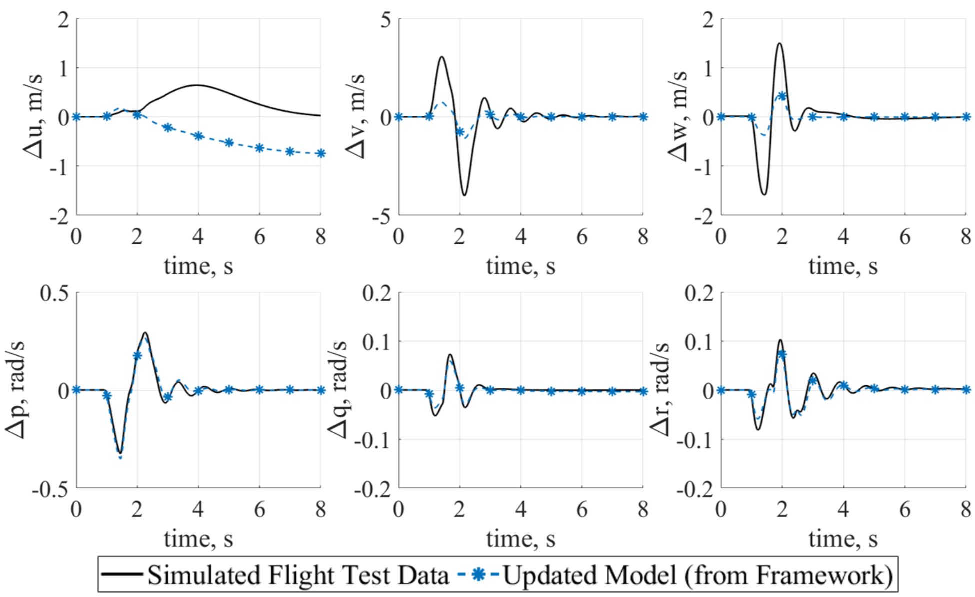

Figure 2.16: System response of updated aircraft model generated using the Tuned Model Method for the 10% increased mass (Modification 1) configuration with no wind and no signal noise, showing good agreement between the two.

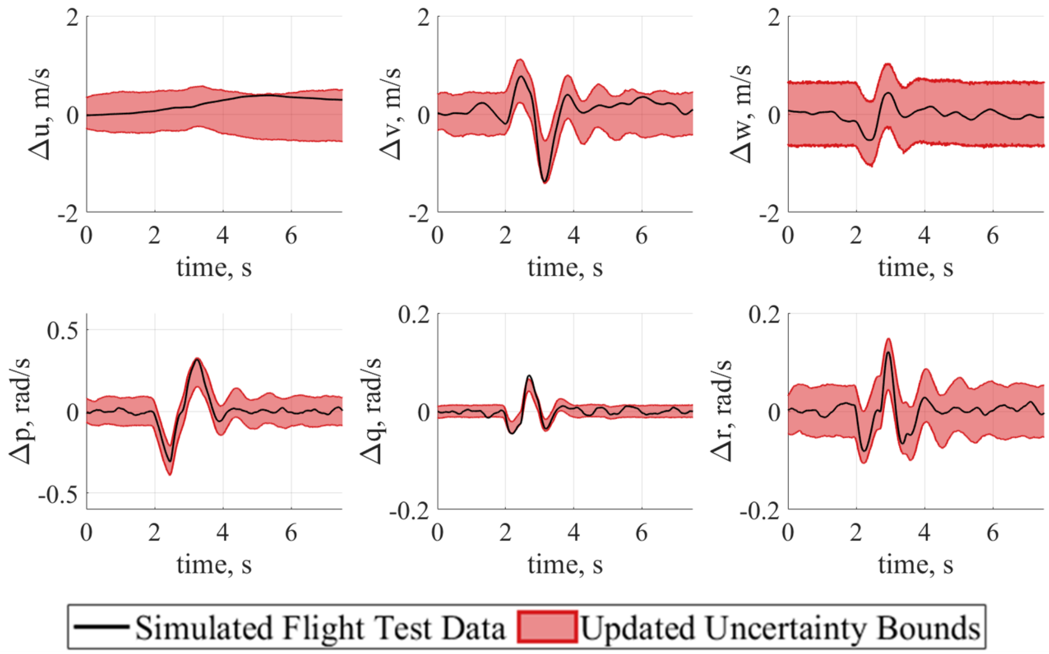

Figure 2.17: Simulation results generated using the Tuned Model Method for the equally distributed mass modification (Modification 1), encapsulating the simulated flight test data for 94% of the data points.

Table 2.2: Comparison of Estimated Performance Bounds Metric for GTM Modifications

Modification	Tuned Model Method	Baseline Model Method
10% Increase in Mass	94%	—
10% Increase in Mass and Change In CG	77%	98%
10% Increase in Mass and Large Change In CG	19%	21%

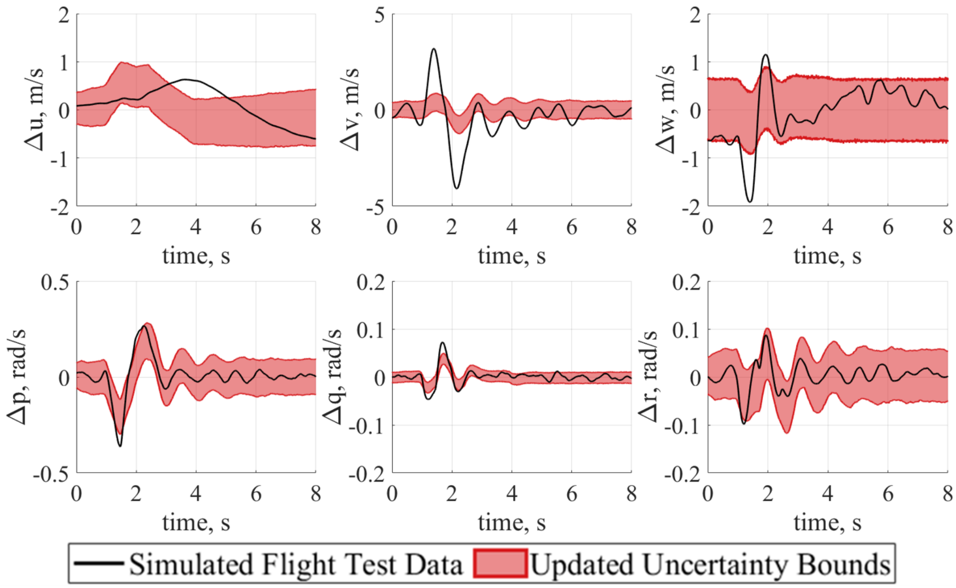

Figure 2.18: Simulation results generated using the Tuned Model Method for the distributed mass modification with change in center of gravity location (Modification 2), which do not fully encapsulate the simulated flight test data, only containing 77% of the data points.

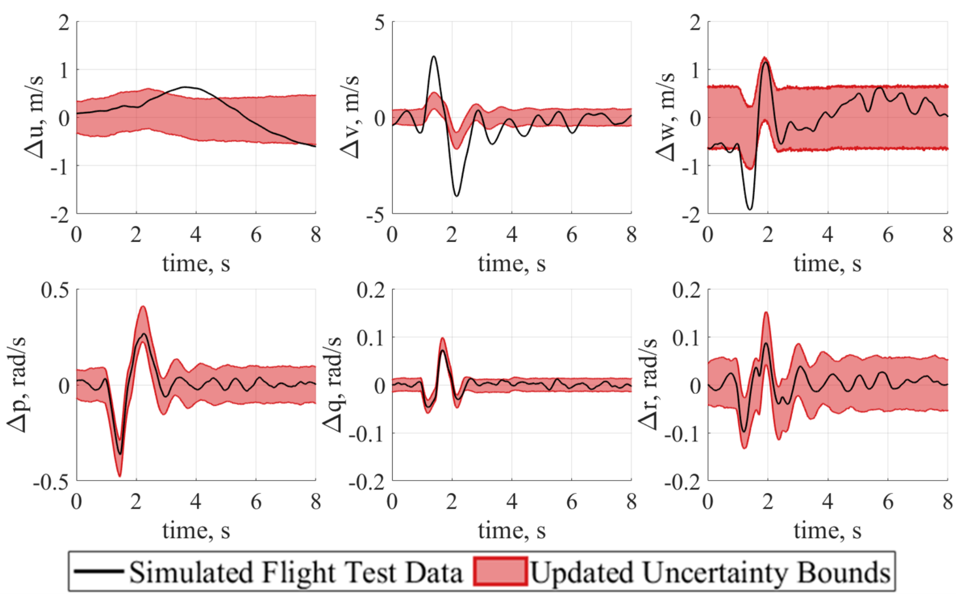

Figure 2.19: Subsection of simulation results generated using the Baseline Model Method for the distributed mass with change in center of gravity modification (Modification 2), which encapsulate more of the simulated flight test data with 98% of the total data points, including those not pictured, contained.

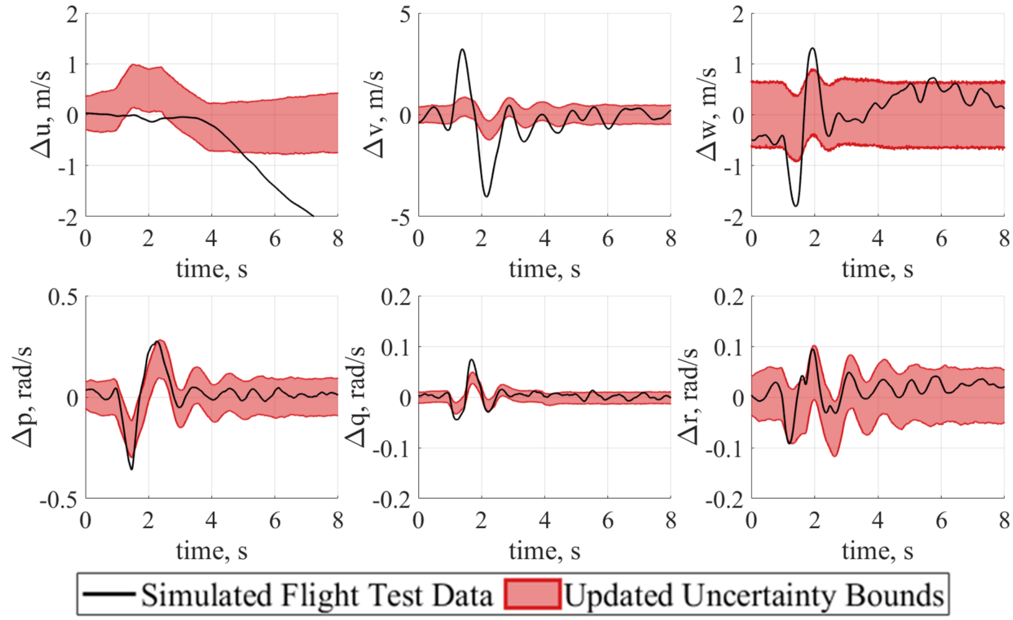

Figure 2.20: Simulation results generated using the Tuned Model Method for the unequally and unrealistically distributed mass modification (Modification 3), which do not fully encapsulate the simulated flight test data, containing only 19% of the data points.

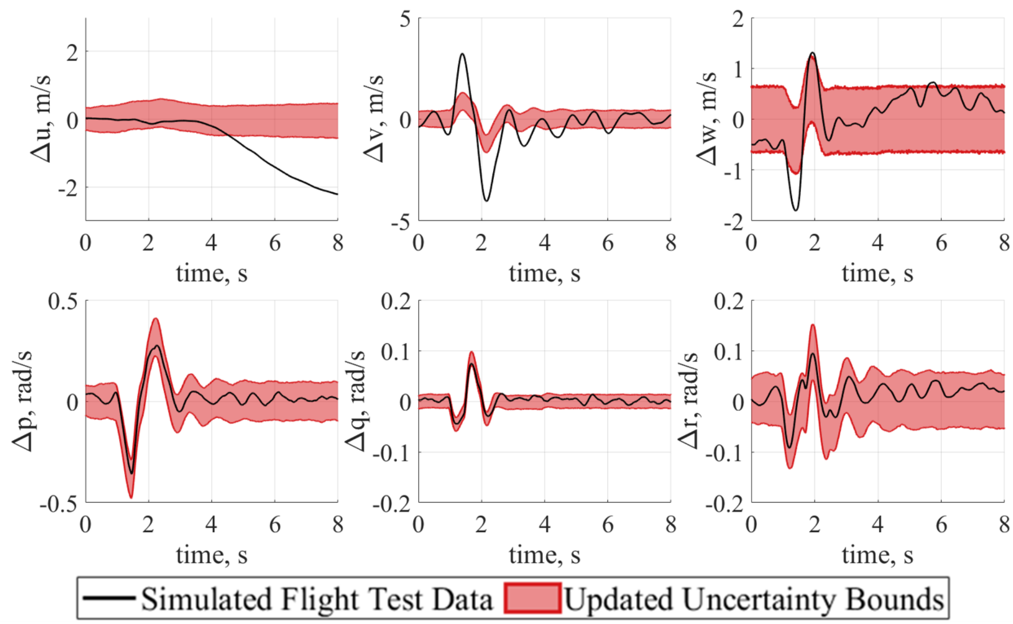

Figure 2.21: Simulation results generated using the Tuned Model Method for the distributed mass modification with large change to center of gravity location (Modification 3), which do not fully encapsulate the simulated flight test data, containing only 21% of the data points.

2.6.3 Validation of Uncertainty Estimation Methods

Along with estimating the performance of modified aircraft configurations, estimating the model form uncertainty for a higher fidelity model of this configuration can also aid the certification process. Because we are using simulated flight test data, it is possible to obtain flight test data for the modified configurations that would otherwise be unavailable. Using the same uncertainty estimation method described in Section 2.3, the true uncertainty for the modified configuration can be calculated. For the first modification of equally distributed mass, the estimated performance bounds generated by the Tuned Model Method are quite similar to the uncertainty bounds calculated by simulating the actual modified configuration, shown in Fig. 2.22. For most of the maneuver, the two bounds are almost identical.

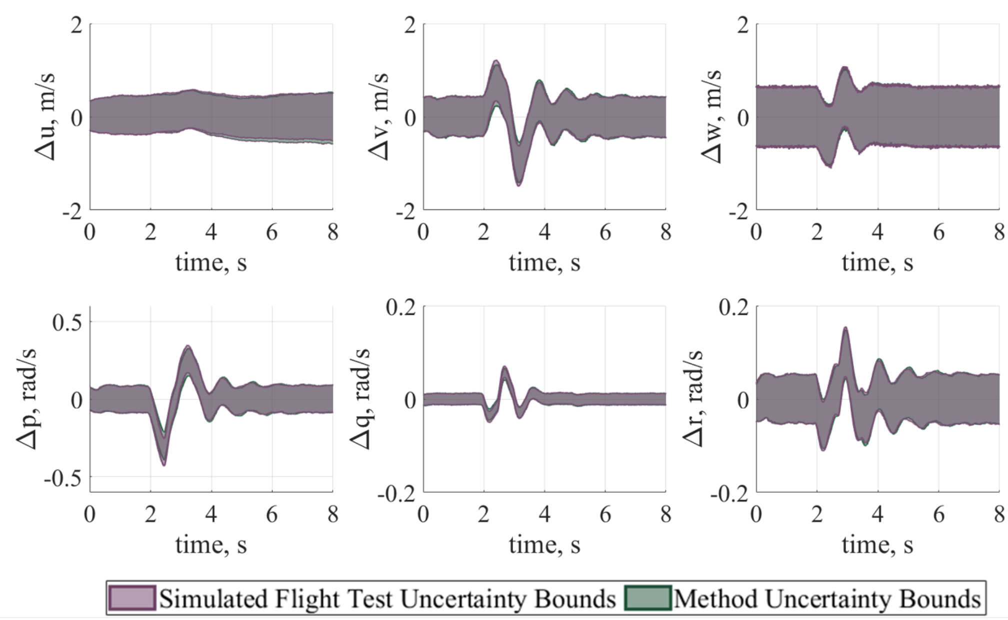

Figure 2.22: Simulation results for the Tuned Model Method uncertainty bounds, green, compared to true uncertainty bounds, purple, for the equally distributed mass modification (Modification 1).

However, when the Tuned Model Method is used to estimate the uncertainty bounds for the distributed mass configuration with change to the center of gravity location, as shown in Fig. 2.23, the estimated uncertainty bounds are significantly different than the true uncertainty bounds, particularly in the forward velocity, Δu, but with differences in the other states. The estimated uncertainty bounds generated using the Baseline Model Method show an improvement, capturing more of the overall trend and magnitude of the uncertainty bounds calculated from the modified configuration, seen in Fig. 2.24.

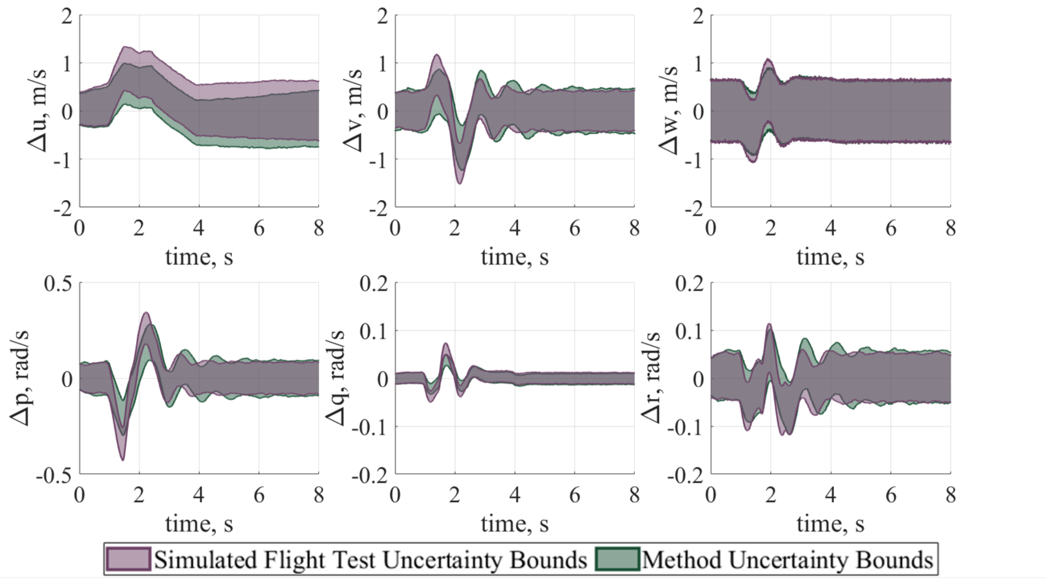

Figure 2.23: Simulation results generated using the Tuned Model Method uncertainty bounds, purple, compared to true uncertainty bounds, green, for the distributed mass modification with change in center of gravity location (Modification 2).

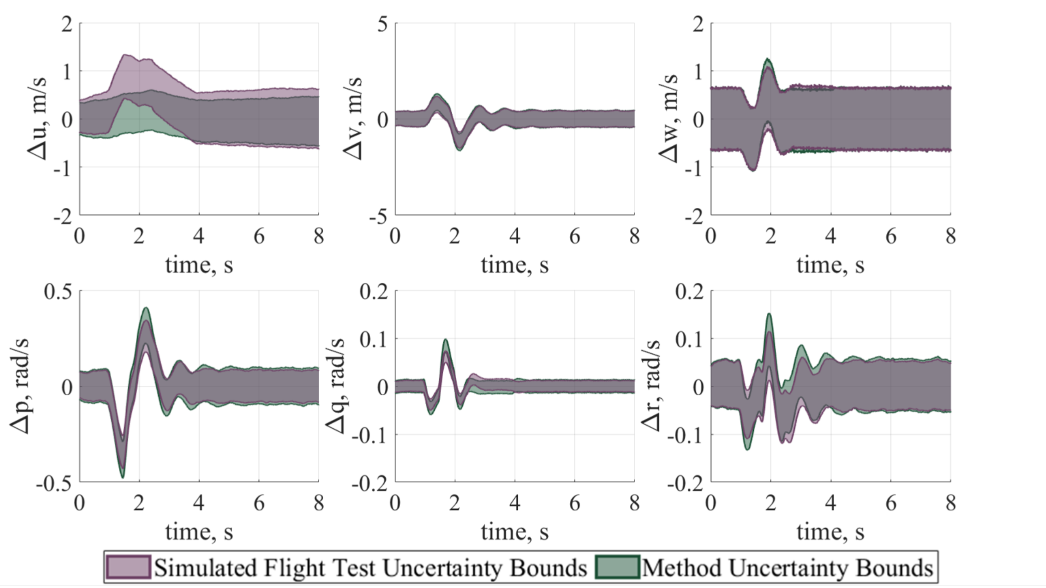

Figure 2.24: Simulation results generated using the Baseline Model Method uncertainty bounds, purple, compared to true uncertainty bounds, green, for the distributed mass modification with change in center of gravity location (Modification 2).

2.7 Summary and Conclusions

A framework to estimate the performance and associated uncertainty bounds for modified aircraft configurations without requiring flight test or other high fidelity data of the modified configuration is introduced. This framework includes two methods to estimate the uncertainty of the modified configurations based on the uncertainty calculated for the nominal configuration. The first uncertainty estimation method, the Tuned Model Method, assumes that the model tuning for the nominal configuration is still valid for the modified configuration and that no additional uncertainty is introduced, whereas the second method, the Baseline Model Method, does not make this assumption and calculates larger uncertainty bounds relative to the baseline model in order to capture more of the modification dynamics. These methods are designed independent of the data collection method (wind tunnel, CFD, simulation, or flight test) as well as the model form (linear, non-linear) of the aircraft model.

These methods are then applied using data from the Generic Transport Model (GTM), a research aircraft operated by NASA Langley. A high fidelity simulation is used to create simulated flight test data as well as linearized models. Three modifications are examined, the addition of an equally distributed mass, the addition of a distributed mass with a small change in center of gravity location, and the addition of a distributed mass with larger change in center of gravity location. The equally distributed mass is modeled in the baseline model, whereas the two mass distributions with changes in center of gravity locations is not fully captured using the linear model by neglecting the changes in the moments of inertia.

The Tuned Model Method is adequate at predicting both the performance and uncertainty of the equally distributed mass modification but does not fully capture the performance or uncertainty for the modification with a mass increase and a small change in center of gravity location. The Baseline Model Method better captures the performance of this modification and provides a more accurate uncertainty profile. Although the results are not as accurate for the case where there is a mass increase and a much larger change in center of gravity location, the differences could indicate that the framework is not applicable for this large of a modification because the uncertainty in the moments of inertia of this modified configuration is not captured by the uncertainty estimate.

The ability of the framework to predict the performance and associated uncertainty bounds of modified aircraft configurations without requiring flight test data of the modifications could have a significant impact on future certification by analysis work. Two current barriers to certification by analysis are the certainty that the calculated results are the same level of accuracy as flight test data and that the uncertainty in the calculated results be quantified. This framework addresses both concerns, providing a critical step towards certification by analysis.

Additional work includes further defining the range of applicability of the framework and the two included methods, both in terms of size and type of aircraft modifications. The range of applicability of these methods is especially important when considering the use of this framework to supplement or reduce flight testing or when considering certification by analysis. These methods will also be applied to NASA's X-57 Maxwell aircraft, which already incorporates several modifications. By using a manned aircraft, the performance predictions can be directly applied to existing airworthiness certification criteria, enabling evaluation of the methods to predict aircraft performance at a suitable level.

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. Special thanks to Dave Cox of NASA Langley Research Center's for his assistance in updating the GTM Design Simulation.

Bibliography

[1] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commercial Derivative Aircraft Acquisitions," Masters thesis, Knoxville, TN, May 2003.

[2] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, March 2010.

[3] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2021. URL https://www.ecfr.gov/.

[4] American Institute of Aeronautics and Astronautics (ed.), *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, January 2021. doi:10.2514/4.106231.001, URL https://arc.aiaa.org/doi/10.2514/4.106231.001.

[5] 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, URL https://arc.aiaa.org/doi/10.2514/6.2020-1520.

[6] *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, URL http://www.nap.edu/catalog/12531.

[7] Mehta, U. B., Eklund, D. R., Romero, V. J., Pearce, J. A., and Keim, N. S., "Simulation Credibilty - Advances in Vertification, Validation, and Uncertainty Quantification," NASA TP-2016-219422, November 2016.

[8] 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, URL https://linkinghub.elsevier.com/retrieve/pii/S0045782511001290.

[9] 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, URL http://www.dl.begellhouse.com/journals/52034eb04b657aea,43e225911b944538,340d23ed5c6d1633.html.

[10] 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, URL https://arc.aiaa.org/doi/10.2514/6.2001-1645.

[11] Oberkampf, W. L., DeLand, S. M., Rutherford, B. M., Diegert, K. V., and Alvin, K. F., "Error and Uncertainty in Modeling and Simulation," *Reliability Engineering & System Safety*, Vol. 75, No. 3, March 2002, pp. 333–357. doi:10.1016/S0951-8320(01)00120-X, URL https://linkinghub.elsevier.com/retrieve/pii/S095183200100120X.

[12] Schaefer, J. A., Cary, A. W., Duque, E. P., and Lawrence, S., "Application of a CFD Uncertainty Quantification Framework for Industrial-Scale Aerodynamic Analysis," *AIAA Scitech 2019 Forum*, AIAA 2019-1492, American Institute of Aeronautics and Astronautics, San Diego, CA, Janary 2019. doi:10.2514/6.2019-1492, URL https://arc.aiaa.org/doi/10.2514/6.2019-1492.

[13] Wendorff, A. D., Alonso, J. J., and Bieniawski, S. R., "A Multi-Fidelity Approach to Quantification of Uncertainty in Stability and Control Databases for use in Stochastic Aircraft Simulations," *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2015-3439, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2015. doi:10.2514/6.2015-3439, URL http://arc.aiaa.org/doi/10.2514/6.2015-3439.

[14] Fidkowski, K., Kroo, I., Willcox, K., and Engelson, F., "Stochastic Gust Analysis Techniques for Aircraft Conceptual Design," *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2008-5848, American Institute of Aeronautics and Astronautics, Victoria, British Columbia, Canada, September 2008. doi: 10.2514/6.2008-5848, URL http://arc.aiaa.org/doi/10.2514/6.2008-5848.

[15] Ng, L. W. T., and Willcox, K. E., "Monte Carlo Information-Reuse Approach to Aircraft Conceptual Design Optimization Under Uncertainty," *Journal of Aircraft*, Vol. 53, No. 2, March 2016, pp. 427–438. doi:10.2514/1.C033352, URL http://arc.aiaa.org/doi/10.2514/1.C033352.

[16] Steinkellner, S., "Aircraft Vehicle Systems Modeling and Simulation under Uncertainty," Master's thesis, Linköping University Institute of Technology, Linköping, Sweden, 2011. URL http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-68068.

[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, Dallas, TX, June 2015. doi: 10.2514/6.2015-2329, URL http://arc.aiaa.org/doi/10.2514/6.2015-2329.

[18] Hale, L. E., Patil, M., and Roy, C. J., "Aerodynamic Parameter Identification and Uncertainty Quantification for Small Unmanned Aircraft," *AIAA Guidance, Navigation, and Control Conference*, AIAA 2015-1538, American Institute of Aeronautics and Astronautics, Kissimmee, FL, January 2015. doi:10.2514/6.2015-1538, URL http://arc.aiaa.org/doi/10.2514/6.2015-1538.

[19] Maine, R. E., and Iliff, K. W., "The Theory and Practice of Estimating the Accuracy of Dynamic Flight-Determined Coefficients," NASA RP-1077, July 1981.

[20] Stripling, H., Adams, M., McClarren, R., and Mallick, B., "The Method of Manufactured Universes for Validating Uncertainty Quantification Methods," *Reliability Engineering & System Safety*, Vol. 96, No. 9, September 2011, pp. 1242–1256. doi: 10.1016/j.ress.2010.11.012, URL https://linkinghub.elsevier.com/retrieve/pii/S0951832011000755.

[21] Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2nd ed., No. 245 in Progress in Astronautics and Aeronautics, AIAA, American Institute of Aeronautics and Astronautics, Reston, VA, June 2015.

[22] Montgomery, D. C., *Design and Analysis of Experiments*, eighth ed., John Wiley & Sons, Inc, Hoboken, NJ, 2013.

[23] Denham, C. L., Patil, M., Roy, C. J., and Alexandrov, N., "Applicability of a Framework for Modeling Modified Aircraft Configurations Using Uncertainty," *AIAA Aviation 2021 Forum*, AIAA 2021-2793, American Institute of Aeronautics and Astronautics, Virtual,

August 2021. doi:10.2514/6.2021-2793, URL https://arc.aiaa.org/doi/10.2514/6.2021-2793.

[24] 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, URL https://arc.aiaa.org/doi/10.2514/6.2018-1762.

[25] Jordan, T., Langford, W., and Hill, J., "Airborne Subscale Transport Aircraft Research Testbed - Aircraft Model Development," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA 2005-6432, American Institute of Aeronautics and Astronautics, San Francisco, CA, August 2005. doi:10.2514/6.2005-6432, URL http://arc.aiaa.org/doi/10.2514/6.2005-6432.

[26] Jordan, T., Langford, W., Belcastro, C., Foster, J., Shah, G., Howland, G., and Kidd, R., "Development of a Dynamically Scaled Generic Transport Model Testbed for Flight Research Experiments," *AUVSI Unmanned Unlimited*, 2004.

[27] Murch, A., and Foster, J., "Recent NASA Research on Aerodynamic Modeling of Post-Stall and Spin Dynamics of Large Transport Airplanes," *45th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 2007-463, American Institute of Aeronautics and Astronautics, Reno, NV, January 2007. doi:10.2514/6.2007-463, URL http://arc.aiaa.org/doi/10.2514/6.2007-463.

[28] Cunningham, K., Cox, D., Murri, D., and Riddick, S., "A Piloted Evaluation of Damage Accommodating Flight Control Using a Remotely Piloted Vehicle," *AIAA Guidance, Navigation, and Control Conference*, AIAA 2011-6451, American Institute of Aeronautics and Astronautics, Portland, OR, August 2011. doi:10.2514/6.2011-6451, URL http://arc.aiaa.org/doi/10.2514/6.2011-6451.

Chapter 3

Effect of Model-Form Factors on Framework for Estimating Performance and Associated Uncertainty for Modified Aircraft Configurations

Casey L. Denham
Mayuresh Patil
Christopher J. Roy
Natalia Alexandrov

Note: This chapter is modified from a conference paper presented at the AIAA 2021 Aviation Forum and will be submitted to the Journal of Validation, Verification and Uncertainty Quantification. The author performed the work and wrote the article under guidance from the co-authors.

Abstract

As improvements are made to the accuracy and reliability of modeling and simulation techniques, certification by analysis becomes a more attractive alternative compared to traditional aircraft flight testing. Certification by analysis is especially cost-effective when one considers modifications to a previously certified aircraft. However, it is important that the models and methods used are applicable and accurate throughout the intended use domain. A framework for estimating the performance and associated uncertainty was introduced in an earlier paper. The factors and limitations of this framework for estimating the performance and associated model form uncertainty are explored to determine the range of applicability of the framework, particularly with respect to model form, process and sensor noise, and quality of available flight test data. This paper focuses on the general limitations of the framework due to the effects of increased uncertainty from model-form factors. The effects of these factors on the performance and uncertainty results are demonstrated using NASA's Generic Transport Model aircraft.

3.1 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
δT	=	throttle deflection
δC_*^{base}	=	change in baseline model due to modified configuration, difference between modified configuration and nominal configuration
δC_*^{tun}	=	additional correction due to tuning of modified configuration model
$\delta C_*^{UQ}\|_{base}$	=	uncertainty bounds from model form uncertainty for modified configuration, evaluated about the baseline model
$\delta C_*^{UQ}\|_{tun}$	=	uncertainty bounds from model form uncertainty for modified configuration, evaluated about the tuned model
ΔC_*^{tun}	=	correction due to model tuning, difference between tuned model and baseline model for nominal configuration
$\Delta C_*^{UQ}\|_{base}$	=	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

3.2 Introduction

The aircraft airworthiness certification process has traditionally relied on flight testing to determine whether the system meets the minimum standards of airworthiness, safety of flight, and risk [1]. Organizations tasked with airworthiness certification are required to consider modifications to a previously certified aircraft as an entirely separate aircraft for the purposes of certification [1, 2, 3]. Because these modifications are about the same aircraft, performing time-consuming and expensive flight tests may not be necessary for some modifications.

There is currently interest in certification by analysis or the use of analysis and simulation to supplement or replace flight testing in the certification process in the aviation community - notably by the AIAA Certification by Analysis Community of Interest, which released a set of recommended practices in 2021 [4]. In particular, there is a desire to use analysis and simulation to model modifications to a previously certified aircraft and associated uncertainties [5]. These modified configurations must still be accurately modeled and simulated with limited or no flight test data in order to meet the standards of airworthiness with the same level of confidence [5]. Certification by analysis is already commonly done in the nuclear industry, due to the high risks and costs associated with nuclear power reactor testing [6]. This paper evaluates a framework which uses uncertainty analysis and non-deterministic simulations to estimate the flight performance of modified aircraft configurations without requiring flight test data of the modified configuration. In the future and with additional development, this estimated performance could then be used to reject unsuitable configurations, such as those that do not meet performance standards or have undesired dynamics, or otherwise inform the flight test process.

The range of applicability of any model or method is important, but it is especially important when discussing certification by analysis of safety-critical systems. For aircraft it is important that the dynamics within the flight envelope be within acceptable limits, although the dynamics outside of the envelope, such as stalls and spins, are also important for performance [7, 8]. With the reduction in flight testing for certification by analysis, it is essential that the methods and models used are accurate and applicable throughout the anticipated flight domain. For example, a linear model would not be expected to provide adequate results for a nonlinear system far from the linearization point. When discussing model applicability, the model is validated at a number of points, indicated by ”V”, which create a validation domain, as illustrated in Fig. 3.1 [9]. The validation domain may partially or fully overlap with the application domain, represented as the larger polygon and

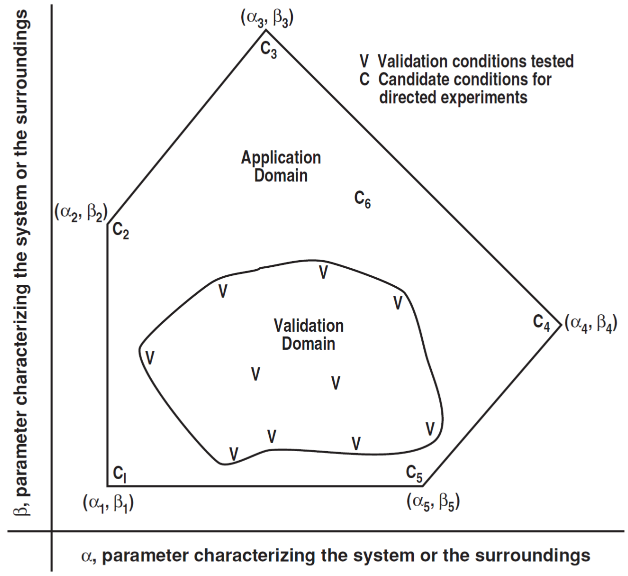

Figure 3.1: Application domain and validation domain[9]. (reproduced with permission)

defined by experimental conditions ”C”, and must be interpolated or extrapolated to fully cover the application domain.

The AIAA Certification by Analysis community of interest believes that analysis used for certification must meet or exceed the accuracy of flight test data to be a suitable substitute [4]. However, many factors can influence the accuracy of flight test data, including steady wind, turbulence, selected sensors, and random and systemic (bias) errors in experimental measurements. The accuracy and uncertainty bounds generated by the uncertainty estimation framework depend on the amount and quality of both the available higher fidelity (flight test) data and the lower fidelity (CFD or wind tunnel) data. These effects are important to capture in order to evaluate the costs associated with achieving a desired accuracy level from the framework and its methods.

This paper revisits the framework for estimating the performance and associated uncertainty of modified aircraft configurations presented in Ref. [10] and explores the initial factors that affect the range of applicability and accuracy of this framework, focusing on the estimation and quantification of uncertainty. Specifically, this paper looks at common scenarios that negatively affect the system identification and uncertainty quantification components of the framework, resulting in poor modeling of the aircraft dynamics and associated uncertainty. Data from NASA Langley Research Center’s Generic Transport Model aircraft are used to illustrate these limitations and the effect they have on the resulting non-deterministic simulation results.

3.3 Framework for Predicting Performance of Modified Aircraft Configurations

One of the goals of this research is to estimate the flight performance and associated uncertainty of a modified aircraft configuration, without requiring flight test data for the modified configuration. For the purposes of this research, a modified configuration is a configuration that differs from the nominal configuration by one or more modifications, such as the addition of payload pods, changes to engine fairings, or wing characteristics. For most aircraft with multiple configurations, there is often a configuration which is considered ”nominal” and is the basis for any modifications. While the nominal configuration will likely have flight test data or other higher fidelity data, these modified configurations may only have limited data available, typically from computational fluid dynamics (CFD) or wind tunnel tests.

Figure 3.2 illustrates the major stages of the framework. First, baseline models of the nominal configuration and any modified configurations are generated using lower fidelity data that might not fully capture all effects, such as CFD. Second, a tuned model of the nominal configuration is generated using system identification of available flight test data. Using these models and the flight test data, model form uncertainty is then estimated. Before proceeding, the models and uncertainty are validated to confirm that the models are adequate for their intended use, using the methods discussed in this paper. Next, one of two methods described in Sections 3.3.4 and 3.3.4 are used to extend the aerodynamic model and uncertainty estimation to the modified configurations. Finally, non-deterministic flight dynamics simulations which account for uncertainty as well as wind turbulence are conducted in order to predict the performance and associated uncertainty bounds of the modified configurations.

3.3.1 Generation of Baseline Models

The first model that is generated for the nominal configuration is the baseline model, which serves as a common denominator for corrections and modifications. This model should ideally be developed using a method which is available for the nominal configuration as well as any modified configurations. For instance, CFD data are available for the nominal configuration and many modified configurations for the AeroStar aircraft used as a research testbed by NAVAIR, but flight test data are not available for all configurations. For the nominal configuration, an example aerodynamic coefficient for this model is indicated by C_*^{base}. Similarly, a baseline model for the modified configuration is also created.

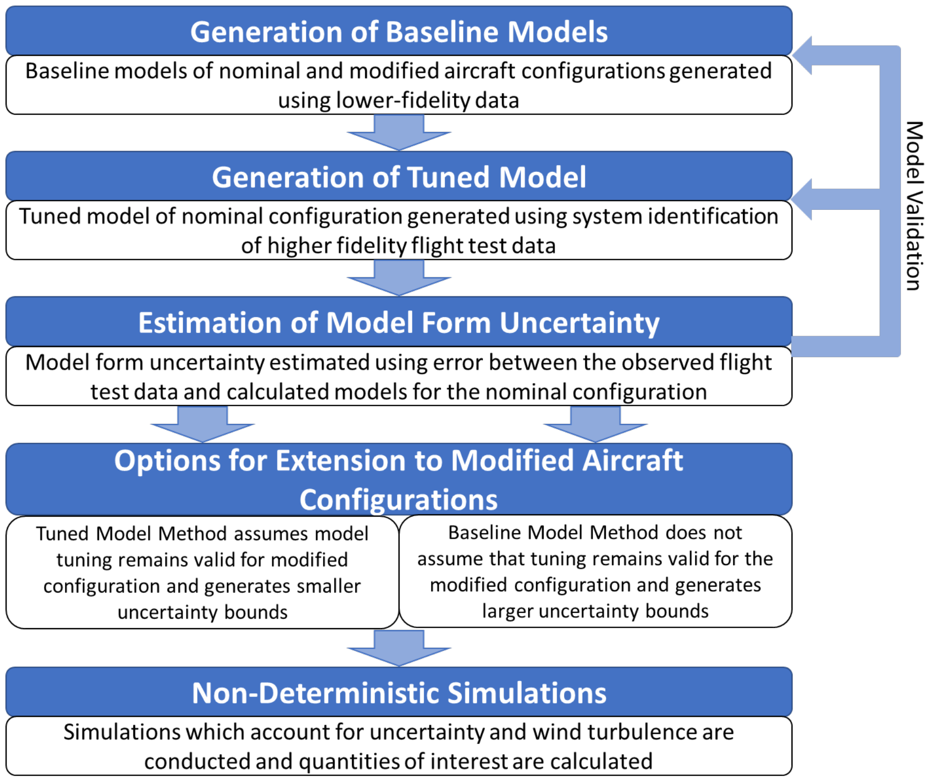

Figure 3.2: Illustration of the developed framework, showing the five main stages.

3.3.2 Generation of Tuned Model

The next model generated for the nominal configuration is the tuned model, which utilizes the most accurate data available, generally flight test data. While this data are more accurate, it may not exist for all configurations, so a tuned model can 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 it is not required to. The difference between the tuned model of the nominal configuration and the baseline model of the same configuration is represented by ΔC_*^{tun}. An improved model of the nominal configuration is then represented by $C_*^{nom} = C_*^{base} + \Delta C_*^{tun}$.

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 the equation error method, the output error method, and the filter error method, which are described in Ref [11].

3.3.3 Estimation of Model Form Uncertainty

The uncertainty of greatest interest is model form uncertainty, or uncertainty due to the difference between the model and the true system. However, the limited availability, poor quality, or inherent noise of these data sources can contribute to additional error in the uncertainty estimation process, which are then included in the model form uncertainty for the model.

To calculate this 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 values from the data. This comparison generates a series of time-independent errors for each timestep, shown as blue dots in Fig. 3.3. A cubic-regression model is then fit to these errors, represented by the black line in Fig. 3.3.Uncertainty bounds are 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, using Eq. (3.1), generating the red lines [12, 13].

$$\hat{y}(x_o) - t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \leq \mu_{y|x0} \leq \hat{y}(x_o) + t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \tag{3.1}$$

$\hat{y}(x_0)$ is the model response about the aircraft state x_0, $t_{\alpha/2,n-p}$ is the probability for 100(1-α) 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, $\mu_{y|x0}$ is the mean error of the model response at the aircraft state, and X is the matrix of observed data. These bounds are shown in Fig. 3.3 as red lines; note that the bounds are modified from the calculation to always include zero error to prevent changes to the model form or tuning within this stage of uncertainty calculations. 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 prediction of bounds where data are sparse, as in Ref. [12]. Because the bounds grow exponentially as they move away from the available data, prediction for aircraft states far from observed values can lead to high uncertainty. This behavior is expected and allows prediction where there are few observed data.

The model form uncertainty can be calculated about both the baseline and tuned models, creating two different uncertainty bounds, as shown in Figs. 3.4 and 3.5. When adding the uncertainty to our model of the nominal configuration, C_*^{nom}, two equations emerge, dependent on whether the tuning correction is used:

$$C_*^{nom}|_{base} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} \tag{3.2}$$

and

$$C_*^{nom}|_{tun} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} \tag{3.3}$$

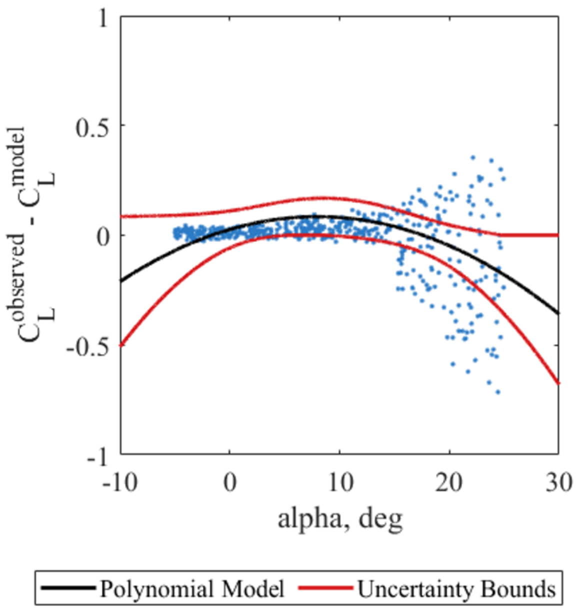

Figure 3.3: Calculation of uncertainty bounds, red, using differences between model and observed data, blue, and a cubic-regression fit of these data, shown in black.

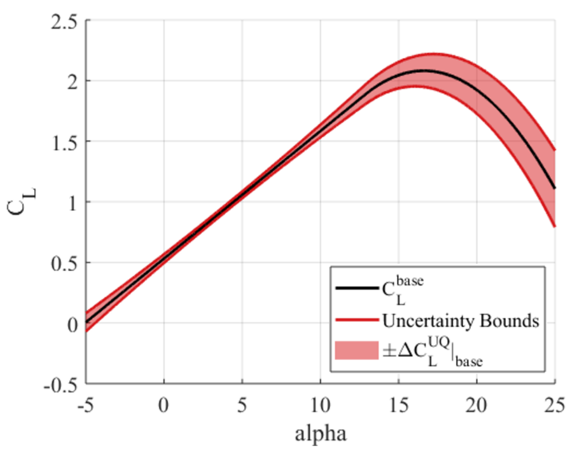

Figure 3.4: Uncertainty calculated about the baseline model.

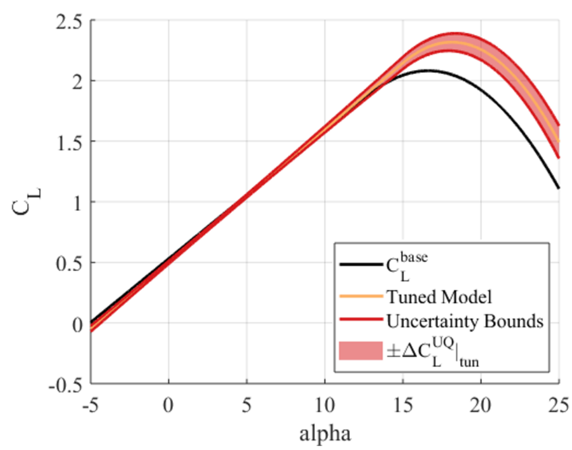

Figure 3.5: Uncertainty calculated about the tuned model. Note that the uncertainty is smaller because the tuned model is closer to the observed data.

3.3.4 Extension to Modified Aircraft Configurations

The first step in modeling a modified configuration is modeling the nominal, unmodified configuration. The framework will be illustrated using a single model term but can be applied to all terms in the aircraft dynamics model. Using the nomenclature described in Ref. [10], C_* represents a generic aerodynamic coefficient, such as the Coefficient of Lift. The nominal configuration of this aircraft can be described using a combination of the baseline model C_*^{base}, model tuning ΔC_*^{tun}, and model form uncertainty ΔC_*^{UQ}. Since we can calculate uncertainty of the nominal configuration about both the baseline and tuned model, there are two related models:

$$C_*^{nom}|_{base} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} \tag{3.4}$$

and

$$C_*^{nom}|_{tun} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} \tag{3.5}$$

Equation 3.4 describes the case where the uncertainty is calculated about the baseline model, $C_*^{UQ}|_{base}$, whereas Eq. 3.5 describes the case where the uncertainty is calculated about the tuned model, $C_*^{UQ}|_{tun}$. Equation 3.5 is more accurate and should always be used, but both equations are given to aid in developing the two methods for modeling for the modified configuration.

When we describe a modified aircraft configuration using the same nomenclature, additional terms appear due to the change in configuration. After including additional model tuning to match flight test data and uncertainty quantification, the final model for the modified configuration can be written in two different ways, corresponding to Eqs. (3.4) and (3.5):

$$C_*^{mod}|_{base} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \pm \delta C_*^{UQ}|_{base} \tag{3.6}$$

and

$$C_*^{mod}|_{tun} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} + \delta C_*^{tun} \pm \delta C_*^{UQ}|_{tun} \tag{3.7}$$

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 (if available) 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 of the nominal and modified configurations, such as wind tunnel or CFD data, δC_*^{tun} and δC_*^{UQ} 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 [10]. The methods differ in the approximation of δC_*^{tun} and δC_*^{UQ} and do not require parameter tuning and uncertainty quantification for the modified configuration. The methods are intended for small and large modifications, respectively. This paper focuses on the general limitations and applicability of the framework and not the applicability of the individual methods to a range of modified configurations. To properly determine and verify the limits on acceptable modifications, flight test data are required for a large spectrum of modified configurations.

Tuned Model Method

The first method to estimate the aerodynamic model and uncertainties of the modified configuration assumes that the total uncertainty for the modified configuration is equivalent to the uncertainty for the nominal configuration and that the model tuning for the nominal configuration also applies to the modified configuration. This assumption is the same as assuming that no additional model tuning is needed for the modified configuration and that the uncertainty bounds of the nominal configuration are valid for the modified configuration. Using Eq. (3.7), this is equivalent to setting δC_*^{tun} and $\delta C_*^{UQ}|_{tun}$ equal to zero.

To generate the updated model used for non-deterministic simulations, the final model can be written as:

$$C_*^{TunedModelMethod} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} \tag{3.8}$$

In other words, only the baseline model for the nominal configuration is updated using the change from the nominal configuration to the modified configuration (δC_*^{base}). As shown in Fig. 3.6 using example artificial data, the updated model, indicated in black with asterisks, is obtained by adding the change due to the modification, δC_L^{base} (shown in blue), and the tuning correction, ΔC_L^{tuned} (shown in orange) to the baseline model, indicated by the solid black line. The uncertainty bounds for the nominal configuration ($\Delta C_*^{UQ}|_{tun}$), shown in red, calculated using the tuned model, are then applied to this model to obtain updated model and uncertainty bounds for the modified configuration. This process is shown in Fig. 3.7 for the example data.

Baseline Model Method

The second method of estimating the uncertainties of the modified configuration assumes that the total uncertainty for the modified configuration is the uncertainty that would occur if there were no tuning for the nominal configuration. This is equivalent to assuming the model tuning correction for the nominal configuration is no longer valid and engineering judgement points toward approximating the total uncertainty for the modified configuration as the uncertainty for the nominal configuration with no tuning. Using Eq. (3.6), this assumption is equivalent to stating that the model uncertainty of the modified configuration is similar to that of the nominal configuration. The updated model for the modified configuration can then be written as:

$$C_*^{BaselineModelMethod} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \tag{3.9}$$

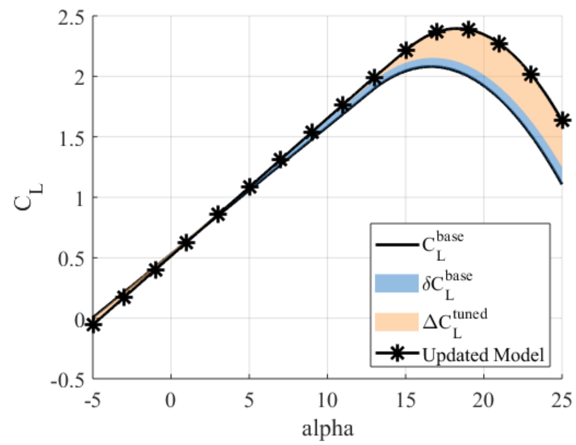

Figure 3.6: Generation of updated model for the modified configuration using the Tuned Model Method with example data. The changes due to the modification, in blue, and the tuning correction term, in yellow, are added to obtain the updated model

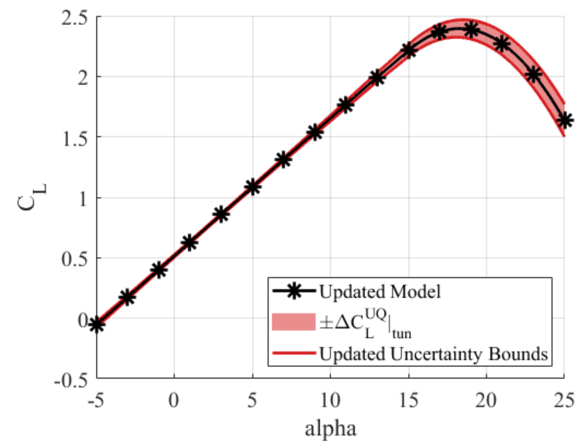

Figure 3.7: Addition of the uncertainty bounds, red, from the nominal configuration to the updated model of the modified configuration using the Tuned Model Method, showing the updated uncertainty bounds using example data.

For this method, the baseline model for the nominal configuration, indicated by the solid black line, has the change due to the modified configuration (δC_*^{base}), shown in blue, added to create the updated model, indicated in black with asterisks in Fig. 3.8 with the example data. Then we use uncertainty bounds ($\Delta C_*^{UQ}|_{base}$) created using flight test data and the baseline model of the nominal configuration, shown in red, as opposed to the tuned model used for the tuned model method. Using the baseline model creates much larger uncertainty bounds that include the effects of model tuning, as in Fig. 4.8.

Use of the Two Methods

The two methods of estimating the uncertainty for the modified configuration provide different levels of conservatism, depending on the characteristics of the model and configuration. The tuned model method, which assumes that the tuning is valid for the modified configuration and leads to smaller uncertainty for the updated model, effectively tunes the model based on the nominal configuration. This assumption leads to less conservative uncertainty bounds about the updated model. An updated model and corresponding uncertainties based on the tuned model method are accurate for modified configurations that are similar to the nominal configuration; i.e., the modifications are minor. However, the baseline model method, which assumes a larger uncertainty based on the (un-tuned) baseline model, aims to give more conservative bounds that will account for larger differences between the nominal and modified

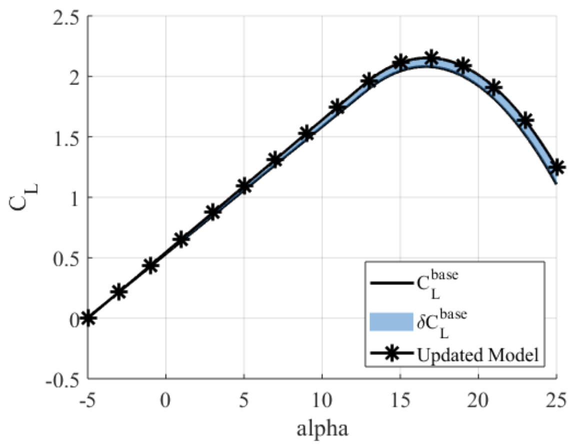

Figure 3.8: Generation of updated model for the modified configuration using the Baseline Model Method. The updated model for the modified configuration has only the changes due to the modification, in blue, added to the baseline model of the nominal configuration.

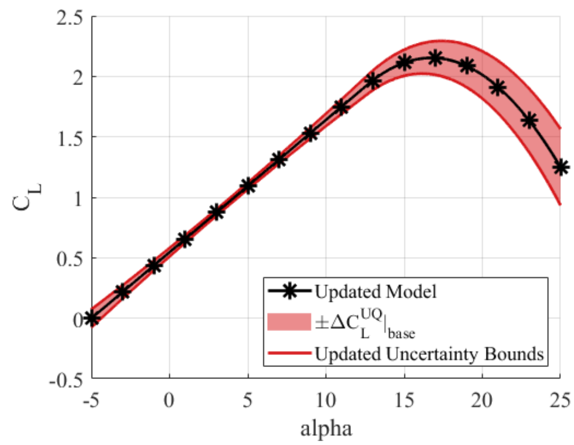

Figure 3.9: Calculation of the total uncertainty for the modified configuration using the Baseline Model Method, with example data. The total uncertainty is the uncertainty from the baseline model.

configurations. The baseline model method does not assume that the tuning correction from the nominal configuration applies to the modified configuration but does assume that the modeling uncertainty is similar. Additional research is required to determine exactly which range of modifications are applicable for each of the two methods.

3.3.5 Non-Deterministic Simulations

Non-deterministic simulations are conducted using the baseline and tuned models while accounting for changes due to modifications as well as model form uncertainty. 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 fully capture the 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 the number of simulation runs required to achieve suitable convergence.

3.4 Evaluation of Uncertainty Bounds Estimation

3.4.1 Example Aircraft System: GTM

NASA Langley Research Center's Generic Transport Model (GTM) aircraft, shown in Fig. 3.10, was chosen as the example aircraft system to demonstrate the proposed framework. The GTM has extensive wind tunnel, CFD, and flight test data and has been used for research including loss of control prediction, spin prediction, and control development [7, 8, 14, 15]. An open-source, high-fidelity, non-linear simulation of the GTM[1], created using a combination of wind tunnel, flight test, and simulation data, was used for this research.

The aircraft simulation is trimmed using a constant true airspeed, which results in the trimmed aircraft states in Table 3.1. Although the simulation includes many control inputs, only elevator, rudder, and aileron deflections are used for this research, with all other surfaces kept at the zero position. All simulation and uncertainty results are shown as deviations from the trimmed aircraft state and surface deflections. The simulation includes a wind turbulence model, enabling the simulation of flight test data with process noise, as well as models of the aircraft sensors, enabling simulation of flight test data with sensor noise. Using this simulation, we created separate simulated flight test data segments for system identification, uncertainty quantification, and uncertainty validation. Because this is simulated data, flight test data can also be created for the modified configurations, enabling a direct comparison of results.

Figure 3.10: NASA Langley's GTM aircraft during a flight test [8].

Table 3.1: GTM Trim States and Deflections

State	Trim Value
u	50.2 m/s
v	0 m/s
w	2.59 m/s
p	0 rad/s
q	0 rad/s
r	0 rad/s
ϕ	0 rad (0 deg)
θ	0.05 rad (2.86 deg)
Deflection	Trim Value
δ_e	2.45 deg
δ_r	0 deg
δ_a	-0.39 deg
δ_T	40.6%

[1] Available at: https://github.com/nasa/GTM_DesignSim

3.4.2 Analysis and Uncertainty Quantification

For the GTM aircraft, both the nominal and modified configuration models come from the simulation, which is then linearized at a given trim condition. To mimic the errors that would typically exist in wind tunnel or simulation data and to account for using the same simulation for flight test data, an artificial trim offset was applied to the system when calculating the baseline models. Additionally, only the longitudinal and lateral components of the equations of motions are used to create the model, neglecting any cross terms. This model form was selected to simulate a lower-order aerodynamic model with specific terms neglected. The modified configurations are created by changing components in the simulation, such as mass or inertial properties.

Simulated flight test data are created using the simulation, including wind and sensor noise, using control inputs generated by the user. The tuned model is created using the output error method of system identification, using the codes associated with Ref. [11]. Although any system identification method could be selected, the output error method was chosen for its ease of use and generally good results.

A second set of simulated flight test data are used for uncertainty quantification and estimation, allowing a range of control inputs and aircraft states throughout the area of interest. The error is estimated by comparing the difference between the model and time derivatives of the flight test data and fitting a polynomial equation to the data.

For much of our analysis in this paper, we will be comparing the calculated uncertainty bounds from a nominal condition (low winds, low sensor noise, all states measured) to an offset condition. These bounds exist in a multi-dimensional space so they will be shown as slices about the trim for each of the aircraft states and inputs. The rate of change in upward velocity ($\Delta\dot{w}$) was selected to show the change in uncertainty, but the uncertainty bounds for each state will have a similar change.

3.5 Limits on Applicability of Framework

Although we are using high-fidelity simulation data in lieu of flight test data to assess the framework, it can still be difficult to accurately predict the performance of modified configurations. Many situations, including incorrect model form, poor data quality, or limited data quantity, affect the accuracy in system identification and uncertainty quantification. Independent of any modification, these situations can result in models with high associated uncertainty, leading to results that are too conservative to be useful. The modification itself also impacts the applicability and usefulness of the framework, although this is still an area of active research.

3.5.1 Baseline Model Form

One of the most important factors that affects the accuracy of the two methods is the choice of the model form used for the baseline model. For example, a linear model could be formed using body-axis positions, velocities, angles, and angular rates creating a 12×12 system of equations, while another linear model could be formed by separating the lateral and longitudinal dynamics, creating two independent 4×4 systems of equations. Non-linear models can vary from combinations of aircraft states and inputs to combinations of states, inputs, and derivatives.

Missing Single Term in Model Form

If significant terms are missing from the model, such as the term relating downward velocity and pitch angle, the uncertainty will show a high correlation with the state and will have a significant non-zero value. Figure 3.11 shows an example of the system identification results when a model missing the single term relating downward velocity, Δw, and pitch angle, $\Delta\theta$, is fit to the data. Although the overall fit of the data are still satisfactory, Fig. 3.12 demonstrates how the uncertainty analysis shows a strong correlation between the uncertainty bounds for the change in downward velocity, $\Delta\dot{w}$, and pitch angle, $\Delta\theta$. Because of the close relationship between pitch angle and forward velocity, there is also strong correlation in the uncertainty bounds for change in downward velocity, $\Delta\dot{w}$, and forward velocity, Δu. If such a correlation is present in the application of the framework, the term should be added before proceeding.

Missing Many Terms in Model Form

If many terms are missing, the total uncertainty will be large, giving results that are too broad and ambiguous. Figure 3.13 shows the effect on system identification of multiple missing terms in the model, in both the lateral and longitudinal dynamics. Although other terms in the model can account somewhat for the missing terms, the uncertainty will be larger than the nominal case, as shown in Fig. 3.14. This increase is most noticeable when the model form uncertainty is plotted against the changes in control inputs, located in the bottom row of Fig. 3.12.

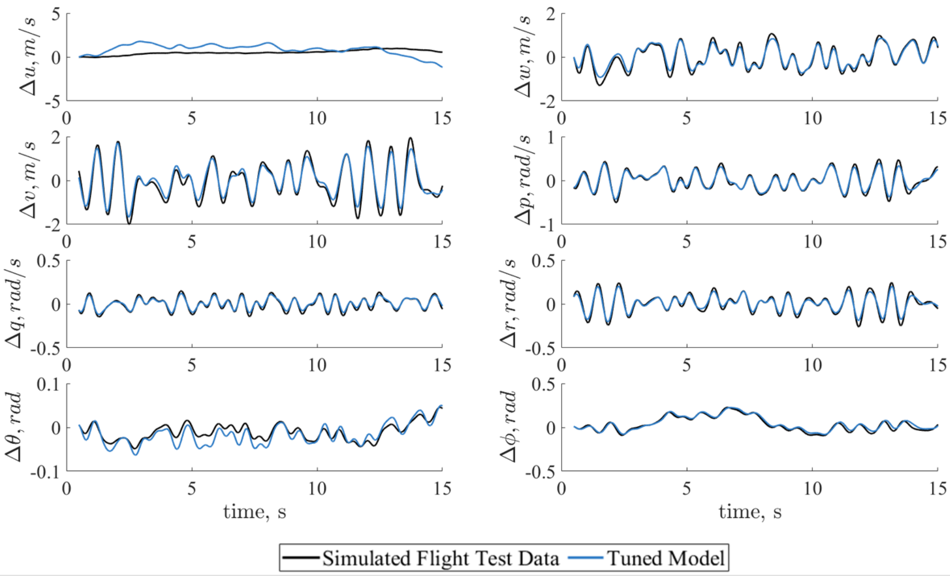

Figure 3.11: Comparison of the simulated flight test data, shown in black, to the tuned model generated with a single missing term, shown in blue.

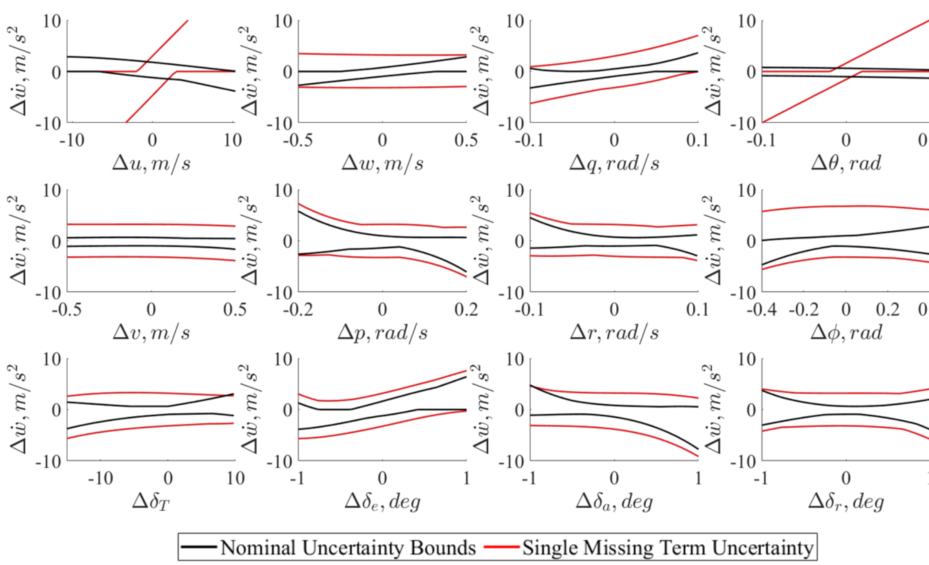

Figure 3.12: Comparison of the nominal uncertainty bounds, shown in black, to the uncertainty bounds generated from a model with a single missing term, shown in red.

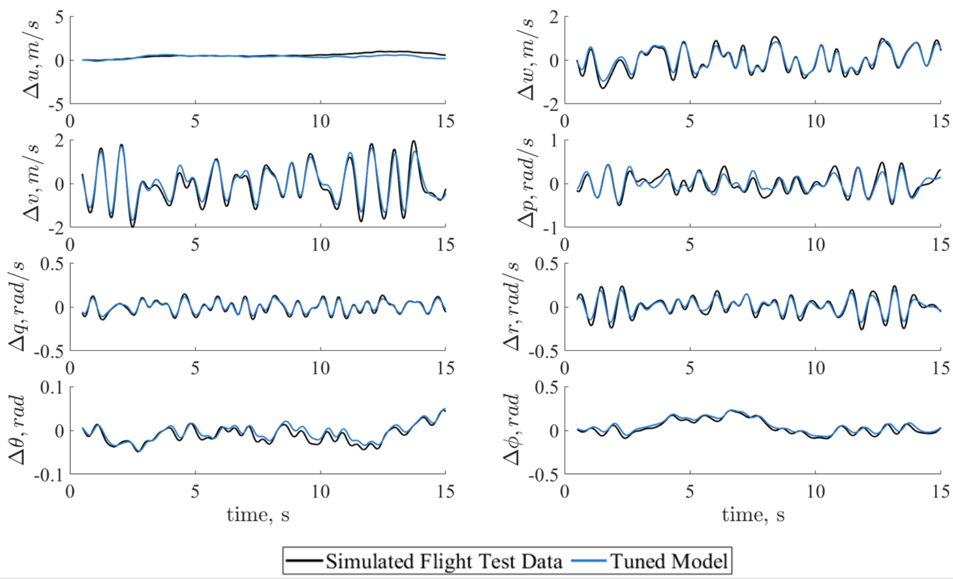

Figure 3.13: Comparison of the simulated flight test data to the tuned model generated with many missing terms.

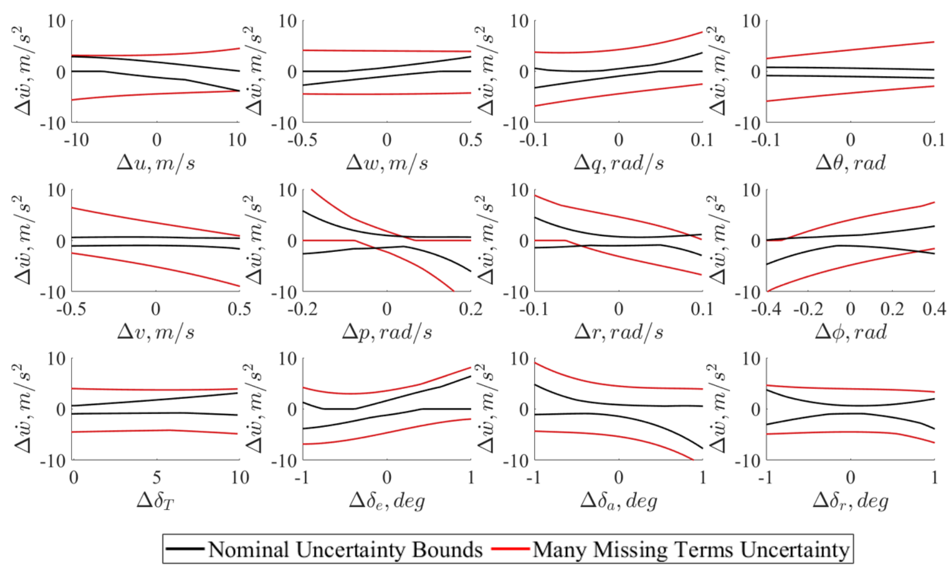

Figure 3.14: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with many missing terms.

3.5.2 Data Quality

Data quality is another factor that can affect the uncertainty estimation, and therefore the applicability of the methods themselves. Three of the key data quality metrics that have a large effect are process noise (noise present in the state derivatives, typically from wind), sensor noise (noise present in the observed states, typically due to bias, accuracy levels, or resolution), and observed states (the states that are measured and collected for further analysis). For the GTM aircraft simulation, a detailed wind model is included, modeling both steady-state and turbulent wind conditions at a variety of wind levels to match those seen in flight. The simulation also includes models of each of the aircraft sensors, such as the Inertial Measurement Unit (IMU) and rate gyroscopes. These sensor models have realistic noise, delay, and range limits to match the research aircraft. Because these instruments are intended for research, their quality is often very high, which serves as a good comparison to illustrate the effects of reduced quality.

High Process Noise

For aircraft flight testing, process noise generally arises due to wind, particularly when wind conditions are not precisely known at each timestep throughout the flight. Flight testing is typically conducted with low, constant-directional wind with a small turbulent component, but it is important to consider the impact of increased wind. Depending on the system identification method used, model tuning can still be generally accurate, as in Fig. 3.15. Although the model has more high frequency content than the simulated flight test data with no wind, the model still follows the trend of the data, with similar peaks and lows. However, additional process noise can increase the uncertainty, even with a good model fit. This is shown in Fig. 3.16, where an increase in the gust turbulence affects the uncertainty across many states. Although wind only directly affects the velocities, the effect on the uncertainty is particularly evident in roll rate, Δp.

High Signal Noise

Another factor which impacts the system identification and uncertainty quantification is high levels of signal noise, typically arising from variations in the sensor readings or interference. As with high process noise, different system identification methods can account for some degree of signal noise. Figure 3.17 shows that the model fit is still quite close to the simulated flight test data. This good fit is due in part to our selection of the output error method for system identification, which is shown to be a good estimator in the presence of sensor noise [11]. However, the uncertainty calculated from simulated flight test data with high signal noise, shown in red, has larger bounds than the uncertainty calculated from the nominal case, shown in black in Fig. 3.18. Although the tuned model is able to closely match the flight test data, the variation in the individual states muddles the calculated error, resulting in some states with smaller bounds but others with larger bounds.

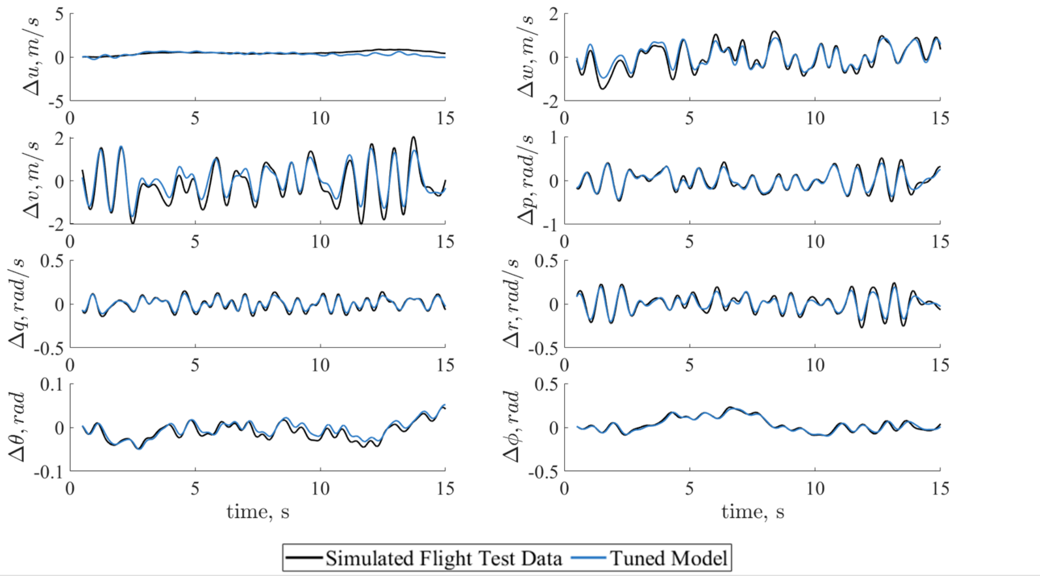

Figure 3.15: Comparison of the simulated flight test data to the tuned model generated with high wind.

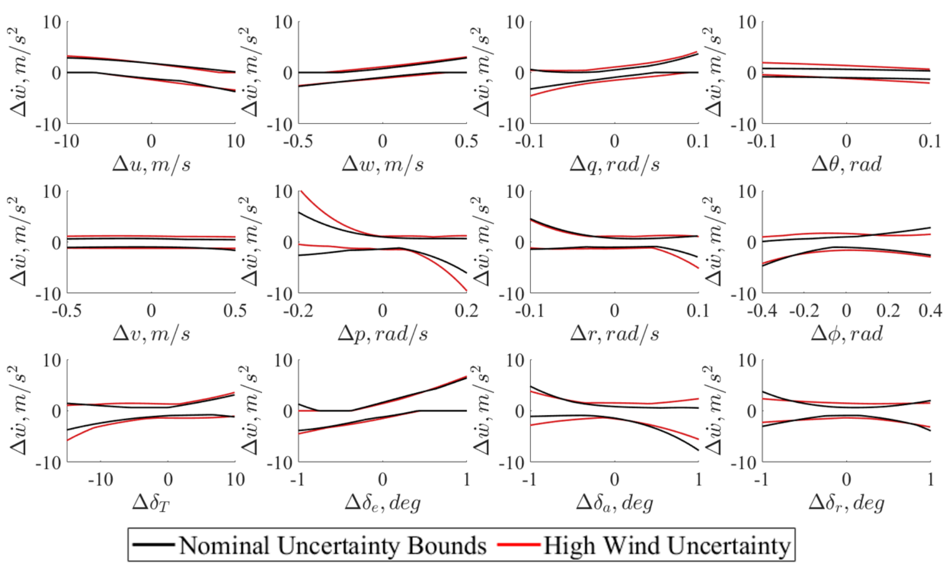

Figure 3.16: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with high wind.

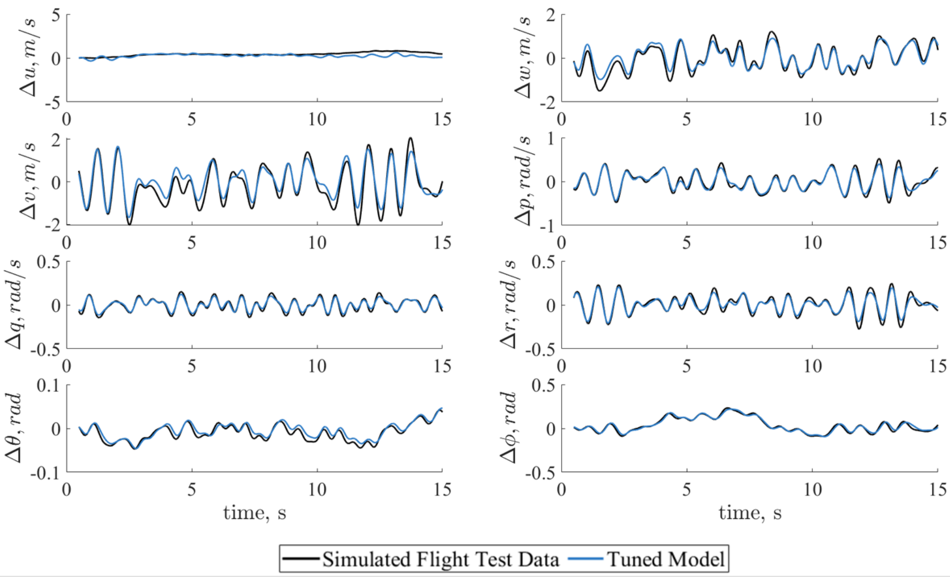

Figure 3.17: Comparison of the simulated flight test data to the tuned model generated with high sensor noise.

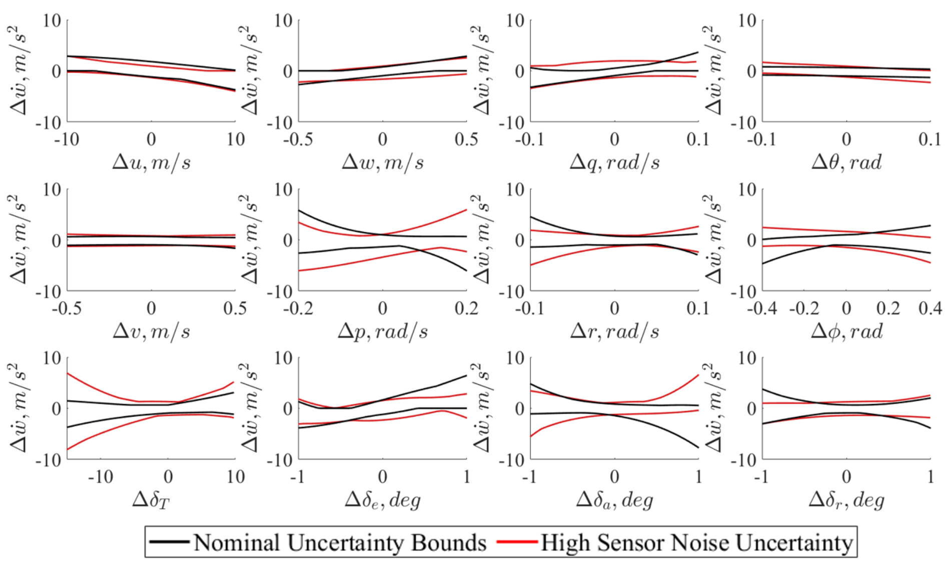

Figure 3.18: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with high sensor noise.

Quantized Signals

Quantization arises when signals are mapped to a finite set - such as when a sensor has poor sensitivity and only outputs values to the nearest unit. In addition to contributing to increased signal noise, this non-linear irreversible process can greatly impact the accuracy of the framework. Figure 3.19 shows an example data segment which has been quantized by rounding to the nearest m/s. For this analysis, velocities were rounded to the nearest m/s, angles were rounded to the nearest 2 deg, and angular rates were rounded to the nearest 2 deg/s. System identification of this data, in Fig. 3.20, shows that the higher frequency content is difficult to recover from quantized data. The error and uncertainty caused by the missing higher frequency content is most evident in forward velocity, Δu, where the observed quantized flight test is mostly constant; the model is only able to provide a best guess of what the true velocity was. When it comes to uncertainty, Fig. 3.21 demonstrates that uncertainty can be quite large in these cases, particularly for the states with high quantization relative to their time histories. For example, the uncertainty bounds for pitch angle, $\Delta\theta$, are larger than the uncertainty bounds in the nominal case, but generally follow the same trend. However, the uncertainty bounds for pitch rate, Δq, have a significantly different trend and are drastically larger than the nominal case.

Limited Observed States

Particularly for small unmanned aircraft, not all states are measured with sensors and are therefore not discretely observed. Although some system identification methods, such as the output error method used in this research, can still identify a model with limited states, the fit is not as accurate as when all states are observed. Figure 3.22 shows the system identification for the GTM, where a model is fit using only velocities and angles. Larger deviations are evident in the angular rates, Δp, Δq, and Δr, where the magnitude of the model has substantial differences.The calculated uncertainty, shown in Fig. 3.23, shows an increase, particularly for the states that were not observed - pitch rate, roll rate, and yaw rate. Because of the choice of $\Delta\dot{w}$ to show the uncertainty, the difference is most obvious in pitch rate, since it is strongly correlated with vertical velocity.

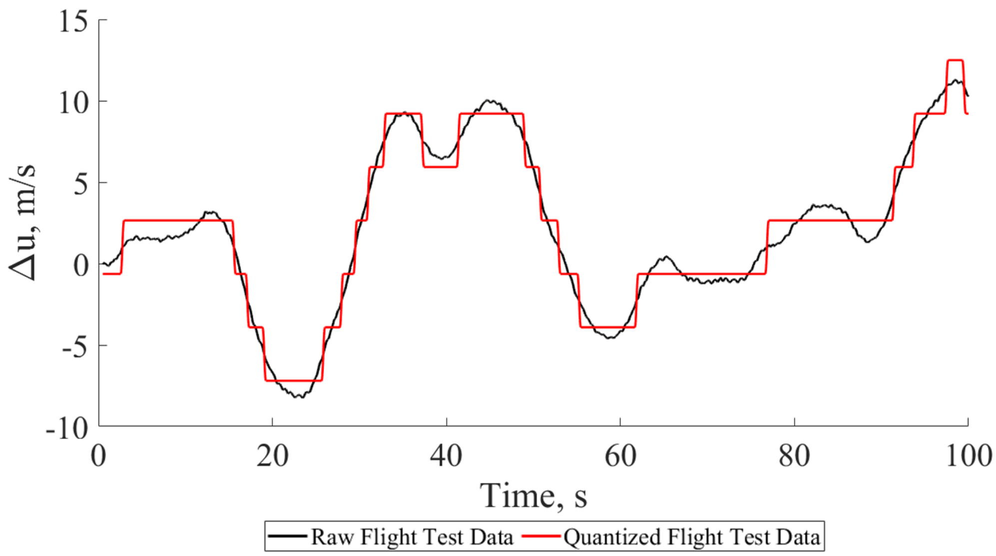

Figure 3.19: Comparison of the raw simulated flight test data to the quantized flight test data, created by rounding to the nearest m/s.

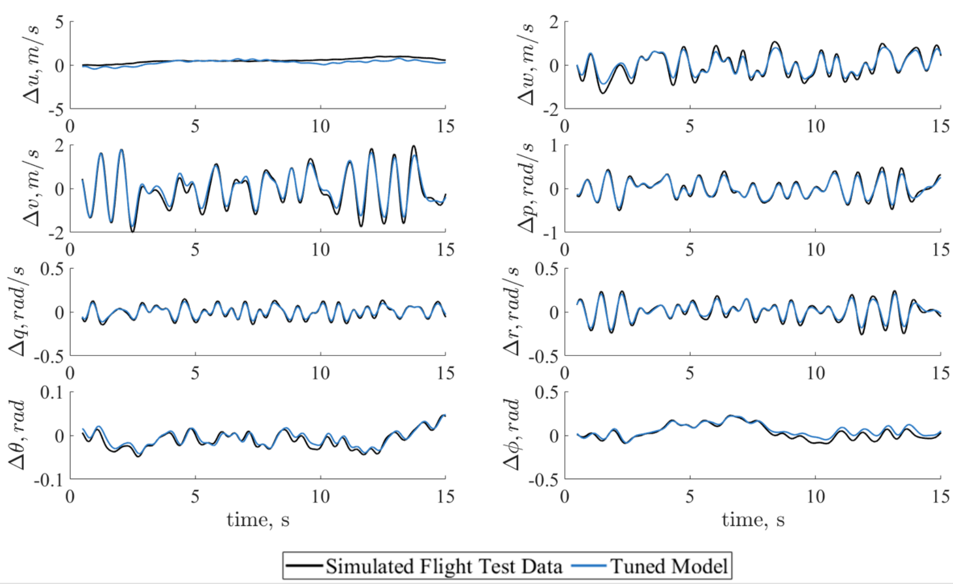

Figure 3.20: Comparison of the simulated flight test data to the tuned model generated with quantized signals.

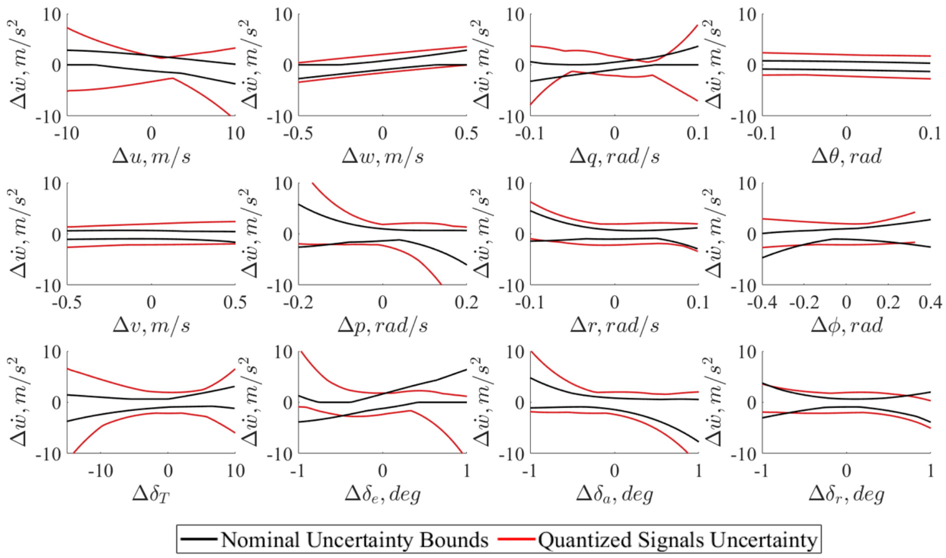

Figure 3.21: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with quantized data.

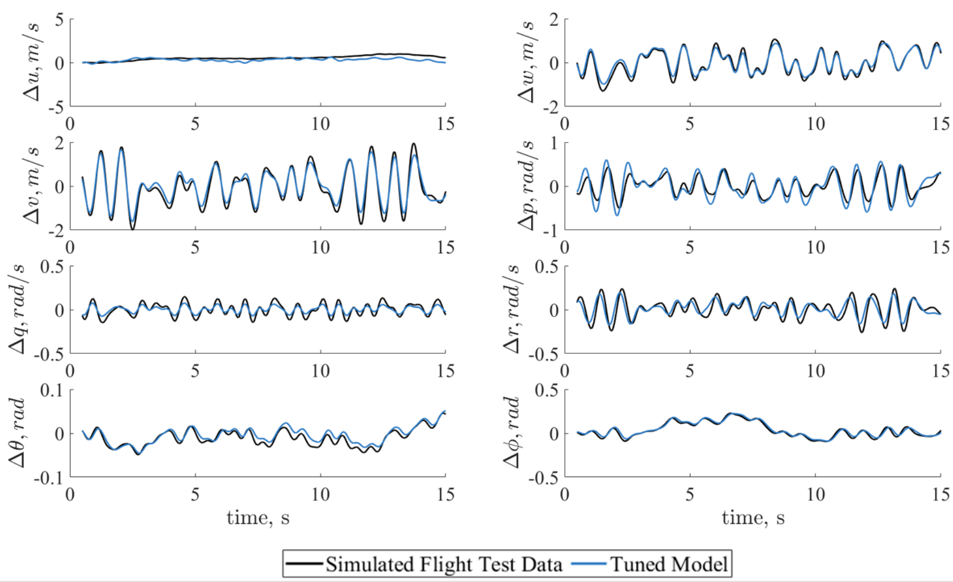

Figure 3.22: Comparison of the simulated flight test data to the tuned model generated with limited observed signals.

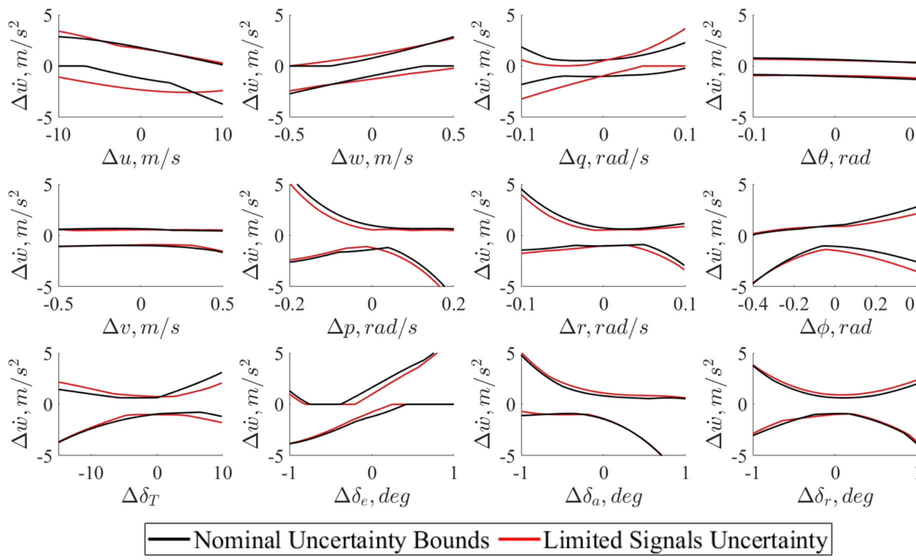

Figure 3.23: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with limited observed states.

3.5.3 Data Quantity

The uncertainty bounds estimation depends on the amount of data points used, with smaller bounds where there are more data and larger bounds in regions where data are sparse. The quantity of the data available, both in sheer numerical size and in relationship to the desired flight envelope, is important to ensuring the estimated uncertainty bounds are representative of the true uncertainty.

Limited Overall Data Availability

Although the overall volume of data are important for the system identification process, we will focus on the effects of limited data on the uncertainty quantification process, since it typically requires more data for accurate bounds. Our uncertainty bounds are dependent on the number of data points, n in Eq. (4.1), so fewer samples results in larger uncertainty bounds. This impact is shown in Fig. 3.24, where the number of samples used for uncertainty quantification was reduced by a factor of 3, creating a dramatic increase in the calculated uncertainty. The limited data affects the relationship between the states and these bounds by changing the correlation, similar to how a linear regression can be fit to sparse data from a non-linear function.

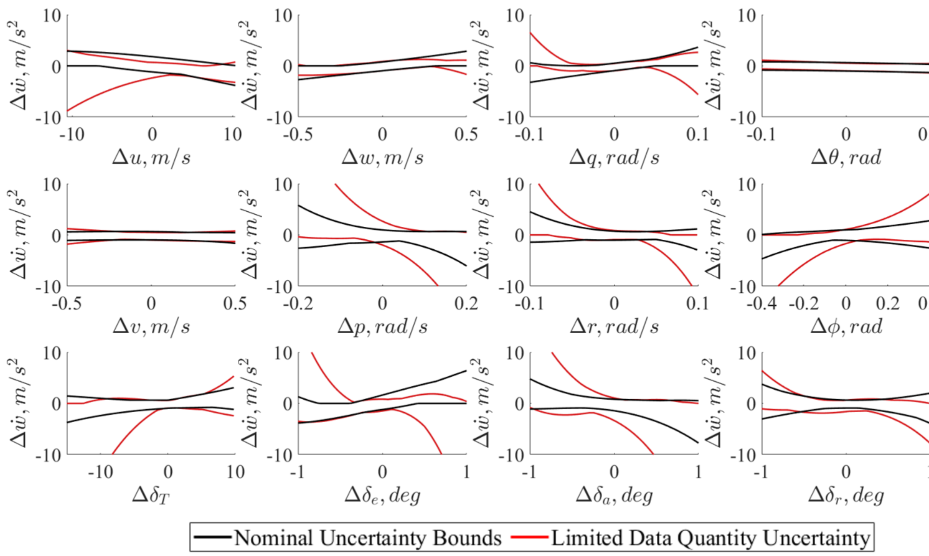

Figure 3.24: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from a model with limited data.

Limited Data in Applicability Domain

In addition to the amount of data available, the location of these data relative to the applicability range is also important. Figure 3.25 shows the effect of extending our existing uncertainty far from the observed data, creating exponential increases in the uncertainty. This exponential effect is seen in the uncertainty bounds for rudder deflection, δ_r, where the bounds rapidly increase away from the trimmed flight condition. The impact of the polynomial fit chosen to model the data are also present; what appeared to be a relatively constant uncertainty bound independent of state can have unexpected values outside of the observed range. This difference in behavior is most clearly shown in the bounds for elevator deflection, δ_e, where the seemingly linear relationship grows into a strong cubic relationship farther away from the observed data. When this uncertainty is used to predict performance outside of the applicability domain defined by the observed data, the 95% confidence bounds on the simulation performance are too conservative to be useful, as shown in Fig. 3.26. The large prediction bounds of the simulation are typical for conditions outside the observed data, since the uncertainty drives the state further from the trim condition which in turn increases the uncertainty.

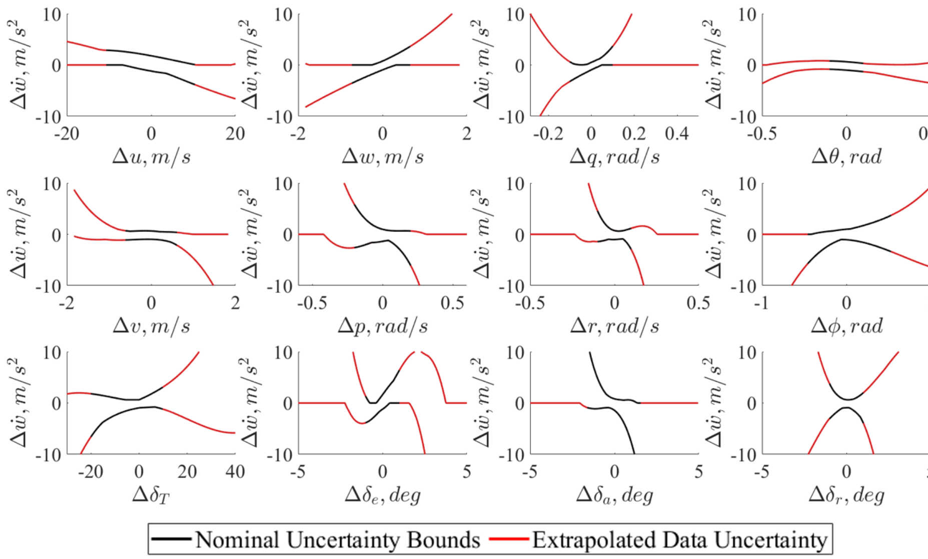

Figure 3.25: Comparison of the nominal uncertainty bounds to the uncertainty bounds generated from extrapolating beyond the observed data.

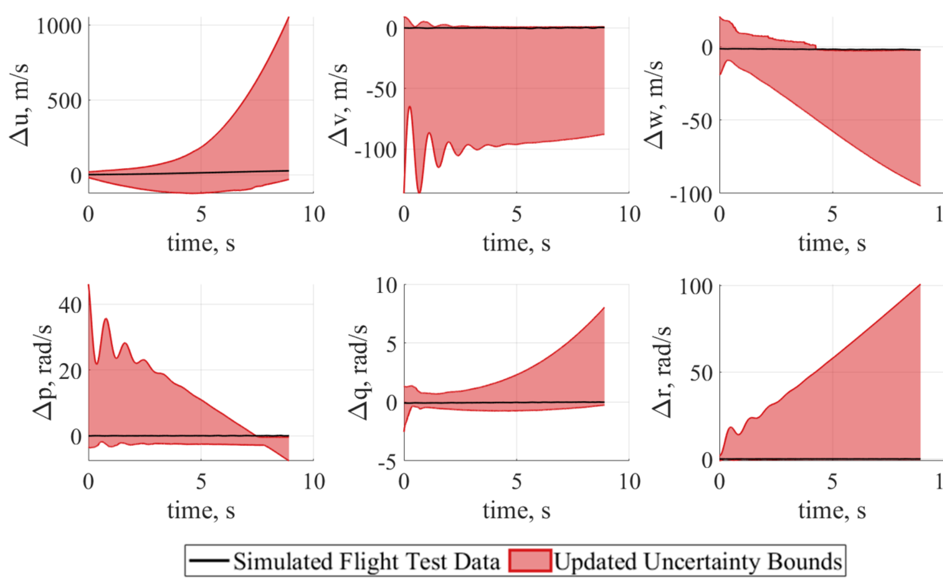

Figure 3.26: Comparison of the simulated flight test data to model results generated using control inputs outside of the applicability range.

3.5.4 Sensitivity to Model Changes

One of the key distinctions between the two uncertainty estimation methods is the ability of the baseline model to adequately represent the modified configuration. For example, if a modification resulted in only higher order changes to the aircraft dynamics, a standard linear model would be unable to model this change. An example of such a change could be using a different material for the wing structure - although the dominant dynamics may not change significantly, higher order effects, such as elastic deformation and load redistribution, could exist in the actual vehicle. These effects would not be shown in the framework results since they are unable to be modeled using the model form selected.

Conversely, if a modification had significant changes to the aircraft dynamics, a linear model may no longer be adequate due to a change in aircraft trim state. As a point of reference, a suitable modification of a 10% increase in mass is shown in Fig. 3.27. Using the less conservative, Tuned Model Method described in Section 3.3.4, the estimated performance bounds, shown in red, adequately capture the performance of the simulated flight test data, shown in black, with 94% of the simulated flight test data points contained within the bounds.

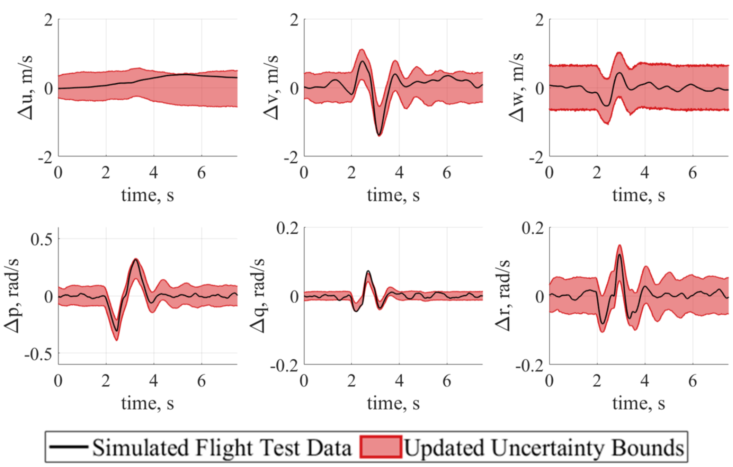

Figure 3.27: Comparison of the simulated flight test data to model results for a suitable modified configuration of a 10% increase in mass.

To demonstrate a dramatic modification, the mass of the aircraft was increased by 10% with a large change to the center of gravity location. Figure 3.28 shows the predicted performance of such a large modification using the Tuned Model method, while Fig. 3.29 shows the predicted performance with the Baseline Model Method. Although there is an increase in the amount of the simulated flight test data included in the estimated performance for the Baseline Model Method, the results are still far below what was seen with smaller modifications. Even with the more conservative uncertainty bounds calculated using the Baseline Model Method, the estimated performance bounds generated using the framework, shown in red, are unable to include the actual dynamics, shown in black, in the prediction for the duration of the maneuver and is unable to capture the pitch rate, an important value for aircraft control, throughout maneuvers.

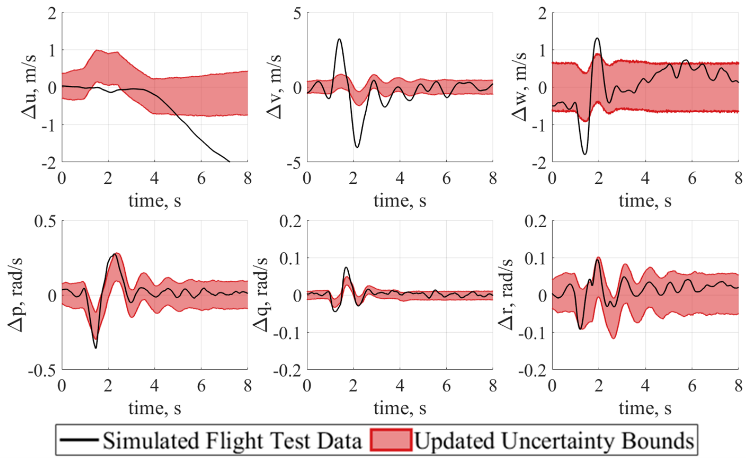

Figure 3.28: Simulation results generated using the Tuned Model Method for the unequally and unrealistically distributed mass modification (Modification 3), which do not fully encapsulate the simulated flight test data, containing only 19% of the data points.

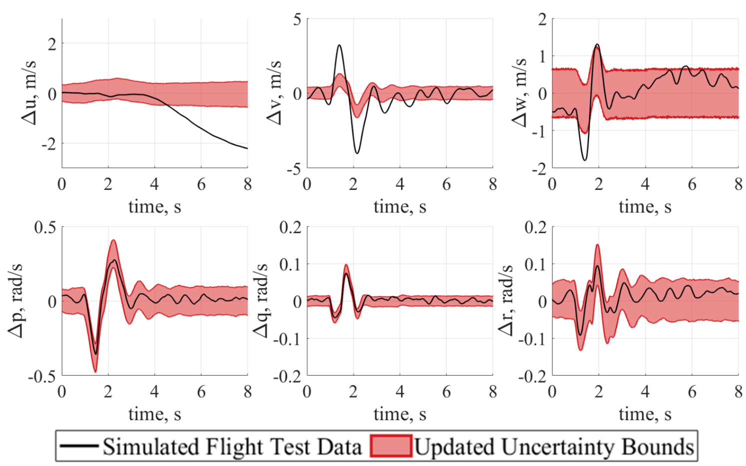

Figure 3.29: Simulation results generated using the Tuned Model Method for the distributed mass modification with large change to center of gravity location (Modification 3), which do not fully encapsulate the simulated flight test data, containing only 21% of the data points.

3.6 Summary and Conclusions

We have evaluated a previously described framework in a number of common situations seen in flight testing and data modeling to determine the applicability and usefulness of the framework. The model form used to model the aircraft dynamics is shown to be important to correctly capturing the uncertainty and dynamics. The quality of the flight test data, including the noise levels and observed states, can also have a significant impact on the framework results. Other factors that affect the framework results include the amount of flight test data and the magnitude of the modification. Additional research into the applicability of each of the two methods, determining the range of acceptable modifications, is an area for future work and would require significant flight test data for a large spectrum of modified configurations. These results will be applied to a real aircraft system in future work, demonstrating that the framework is capable of predicting performance of modified configurations for a realistic system.

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. Special thanks to Dave Cox of NASA Langley Research Center's Dynamic Systems Controls Branch (D316) for his assistance in updating the GTM Design Simulation.

Bibliography

[1] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commercial Derivative Aircraft Acquisitions," Masters thesis, Knoxville, TN, May 2003.

[2] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, March 2010.

[3] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2021. URL https://www.ecfr.gov/.

[4] American Institute of Aeronautics and Astronautics (ed.), *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, Inc.,

Reston, VA, January 2021. doi:10.2514/4.106231.001, URL https://arc.aiaa.org/doi/10.2514/4.106231.001.

[5] 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, URL https://arc.aiaa.org/doi/10.2514/6.2020-1520.

[6] *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, URL http://www.nap.edu/catalog/12531.

[7] Murch, A., and Foster, J., "Recent NASA Research on Aerodynamic Modeling of Post-Stall and Spin Dynamics of Large Transport Airplanes," *45th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 2007-463, American Institute of Aeronautics and Astronautics, Reno, NV, January 2007. doi:10.2514/6.2007-463, URL http://arc.aiaa.org/doi/10.2514/6.2007-463.

[8] Jordan, T., Langford, W., and Hill, J., "Airborne Subscale Transport Aircraft Research Testbed - Aircraft Model Development," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA 2005-6432, American Institute of Aeronautics and Astronautics, San Francisco, CA, August 2005. doi:10.2514/6.2005-6432, URL http://arc.aiaa.org/doi/10.2514/6.2005-6432.

[9] Oberkampf, W. L., and Roy, C. J., *Verification and Validation in Scientific Computing*, Cambridge Univ. Press, Cambridge, England, 2013.

[10] 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, URL https://arc.aiaa.org/doi/10.2514/6.2018-1762.

[11] Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2^{nd} ed., No. 245 in Progress in Astronautics and Aeronautics, AIAA, American Institute of Aeronautics and Astronautics, Reston, VA, June 2015.

[12] 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, Dallas, TX, June 2015. doi:10.2514/6.2015-2329, URL http://arc.aiaa.org/doi/10.2514/6.2015-2329.

[13] Montgomery, D. C., *Design and Analysis of Experiments*, eighth ed., John Wiley & Sons, Inc, Hoboken, NJ, 2013.

[14] Jordan, T., Langford, W., Belcastro, C., Foster, J., Shah, G., Howland, G., and Kidd, R., “Development of a Dynamically Scaled Generic Transport Model Testbed for Flight Research Experiments,” *AUVSI Unmanned Unlimited*, 2004.

[15] Cunningham, K., Cox, D., Murri, D., and Riddick, S., “A Piloted Evaluation of Damage Accommodating Flight Control Using a Remotely Piloted Vehicle,” *AIAA Guidance, Navigation, and Control Conference*, AIAA 2011-6451, American Institute of Aeronautics and Astronautics, Portland, OR, August 2011. doi:10.2514/6.2011-6451, URL http://arc.aiaa.org/doi/10.2514/6.2011-6451.

Chapter 4

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

Casey L. Denham
Mayuresh Patil
Christopher J. Roy
Natalia Alexandrov

Note: This chapter comes from a conference paper that will be submitted to the AIAA SciTech 2023 Forum. The author performed the work and wrote the article under guidance from the co-authors.

Abstract

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 toolbox. We expect the framework to reduce and supplement the flight testing required to show compliance to airworthiness certification criteria for a modified configuration.

4.1 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
$\Delta C_*^{UQ}\|_{base}$	=	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

4.2 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, 2, 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, 9, 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 Ref. [11], 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 [12]. Although many of the flight performance requirements remain unchanged, significant changes would be required in standards for engines and propellers [12]. The X-57 Maxwell project works with regulators to identify regulatory barriers and develop new standards to enable the use of innovative technologies [13, 14]. 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 [14].

We start with a brief overview of the framework from Ref. [11], 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.

4.3 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.

4.3.1 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.

4.3.2 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. 4.1.

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. [15]. For this work, the output error method was chosen due to the ease of implementation.

4.3.3 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. 4.2. 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 in Hale et al. and Montgomery:

$$\hat{y}(x_o) - t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \leq \mu_{y|x0} \leq \hat{y}(x_o) + t_{\alpha/2,n-p}\sqrt{\hat{\sigma}^2 x_0'(X'X)^{-1}x_o} \tag{4.1}$$

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-α) 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, $\mu_{y|x0}$ 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. 4.2 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. [16]. 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. 4.3 and 4.4. In Fig. 4.3, 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 4.4 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.

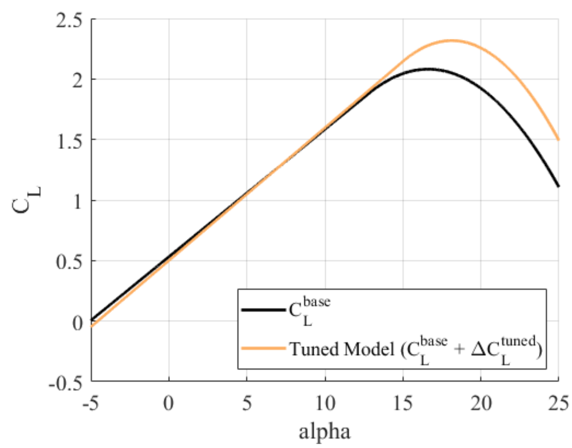

Figure 4.1: Baseline model (black) and tuned model (orange), illustrated using example data.

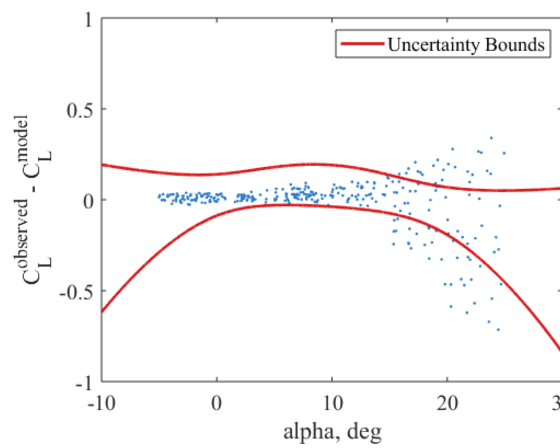

Figure 4.2: Calculation of uncertainty bounds (red), using differences between model and observed data (blue).

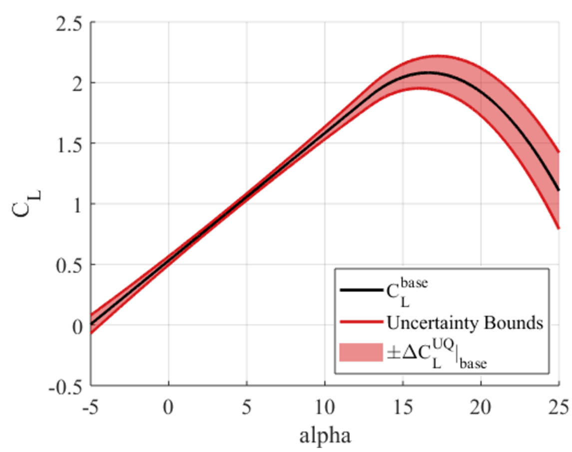

Figure 4.3: Uncertainty calculated about the baseline model.

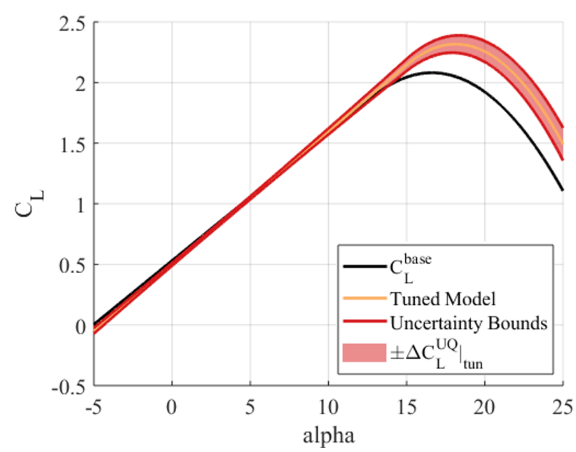

Figure 4.4: Uncertainty calculated about the tuned model. Note that the uncertainty is smaller because the tuned model is closer to the observed data.

4.3.4 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:

$$C_*^{baselinewithUQ} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} \tag{4.2}$$

and

$$C_*^{tunedwithUQ} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} \tag{4.3}$$

Equation 4.2 describes the case where the uncertainty is calculated about the baseline model, $C_*^{UQ}|_{base}$, while Equation 4.3 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 4.2 and 4.3:

$$C_*^{baselinewithUQ,mod} = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \pm \delta C_*^{UQ}|_{base} \tag{4.4}$$

$$C_*^{tunedwithUQ,mod} = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} + \delta C_*^{tun} \pm \delta C_*^{UQ}|_{tun} \tag{4.5}$$

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.

4.3.5 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 4.5, 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

$$C_* = C_*^{base} + \Delta C_*^{tun} \pm \Delta C_*^{UQ}|_{tun} + \delta C_*^{base} \tag{4.6}$$

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. 4.5) and the tuning correction from the nominal configuration (ΔC_*^{tun}, shown in orange). The additive process is shown in in Fig. 4.5 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. 4.6 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.

4.3.6 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

$$C_* = C_*^{base} \pm \Delta C_*^{UQ}|_{base} + \delta C_*^{base} \tag{4.7}$$

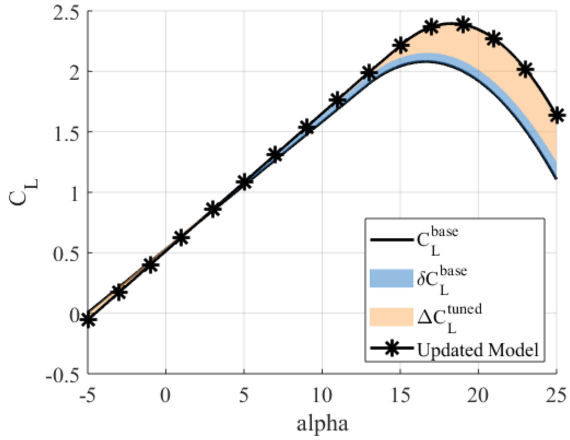

Figure 4.5: Generation of updated model for the modified configuration using Method 1 with example data. The changes due to the modification, in blue, and the tuning correction term, in yellow, are added to obtain the updated model.

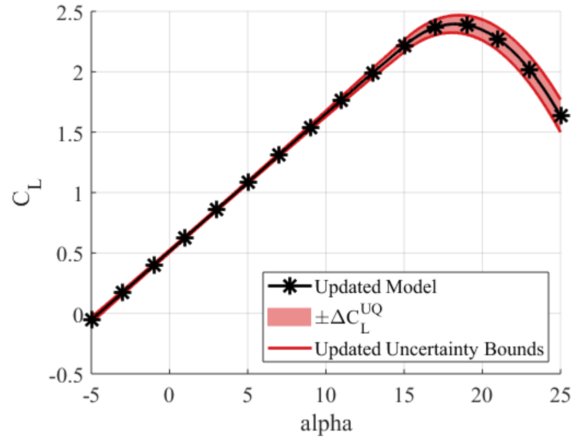

Figure 4.6: Addition of the uncertainty bounds, red, from the nominal configuration to the updated model of the modified configuration using Method 1, showing the updated uncertainty bounds using example data.

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. 4.7) 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. 4.8.

4.4 X-57 Maxwell

The X-57 Maxwell, shown in Fig. 4.9 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 Mods (modifications) to an existing aircraft, incrementally transforming it into an electric aircraft and ultimately including distributed electric propulsion. The Mods are shown in Fig. 4.10.

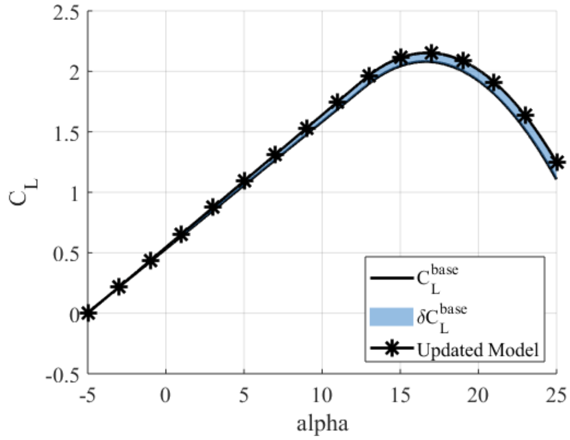

Figure 4.7: Generation of updated model for the modified configuration using Method 2. The updated model for the modified configuration has only the changes due to the modification, in blue, added to the baseline model of the nominal configuration.

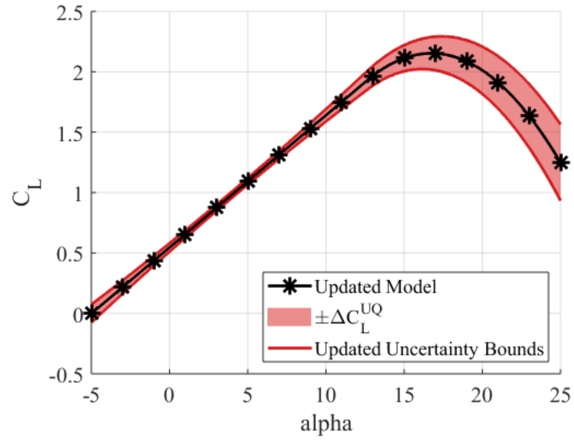

Figure 4.8: Calculation of the total uncertainty for the modified configuration using Method 2, with example data. The total uncertainty is the uncertainty from the baseline model.

The Mods make the X-57 Maxwell a good candidate to explore the use of our framework from Ref. [11] 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 [18, 19, 20]. Much of these data have been put into 6-degree-of-freedom aircraft simulations using MATLAB®'s Simulink®Software [20]. Flight test data are also available for the baseline Tecnam P2006T aircraft, which serves as the Mod-I configuration [20]. However, flight test data for the Mod-II through Mod-IV configurations have not yet been collected, with flight testing planned in the future.

Figure 4.9: An artist's rendering of the X-57 Maxwell aircraft in flight, shown in the Mod IV Configuration.

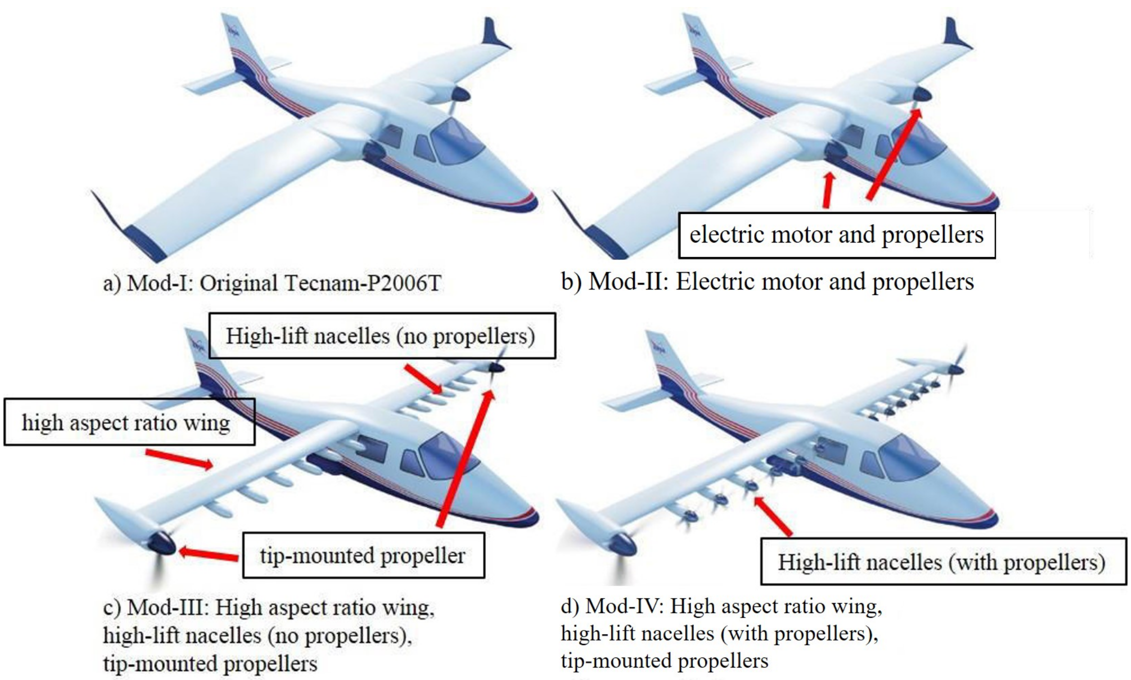

Figure 4.10: Incremental modifications of the X-57 Maxwell, from the Tecnam P2006T to the complete distributed electric propulsion aircraft [18].

4.5 Application and Results

4.5.1 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 [18, 19, 20]. 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 [19]. 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 4.11 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.

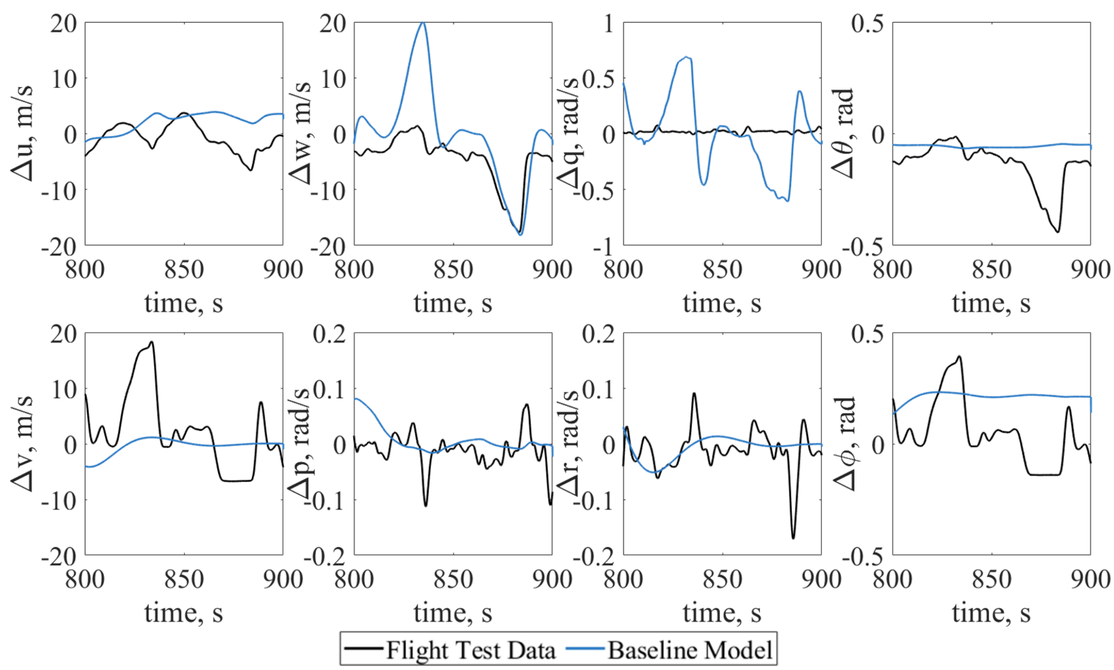

Figure 4.11: Comparison of the baseline model for the Mod-I configuration to flight test data of a Tecnam P2006T.

4.5.2 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. [15].

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 4.12 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. 4.12, 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.

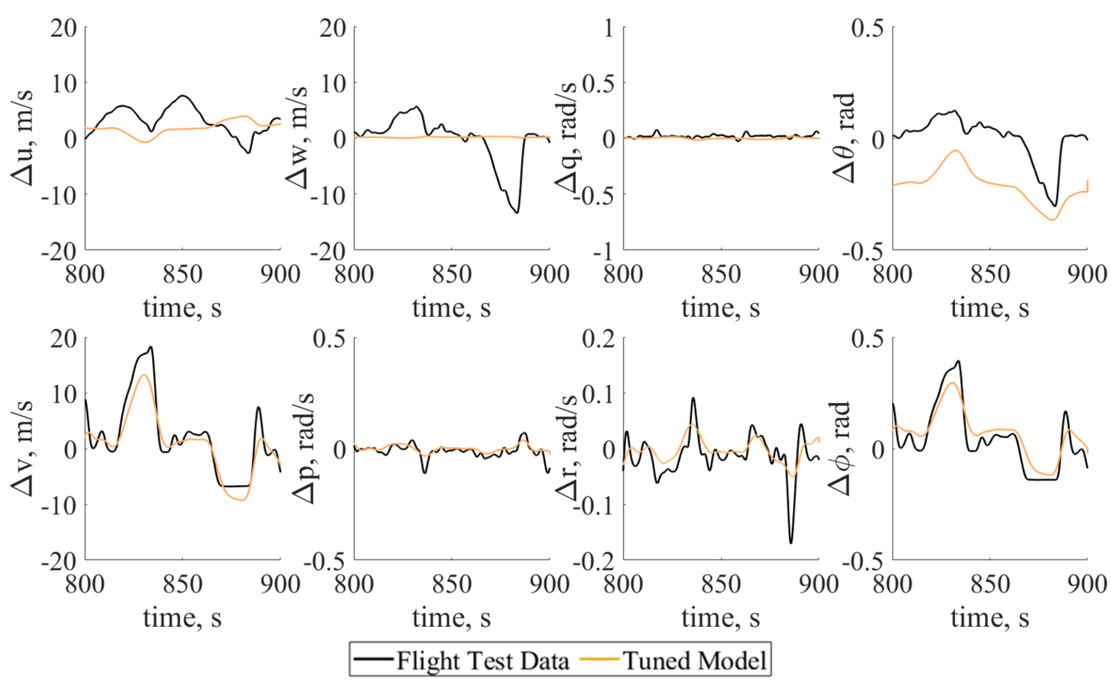

Figure 4.12: Comparison of the tuned model for the Mod-I configuration to flight test data of a Tecnam P2006T, for a section of flight test data containing a maneuver.

4.5.3 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 4.13 shows these errors for vertical acceleration, $\Delta\dot{w}$, as well as the uncertainty bounds calculated using Eq. 4.1. 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. 4.1, using the observed flight test data, as a function of each aircraft state. This creates multi-dimensional uncertainty bounds, which are shown in Fig. 4.13 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.

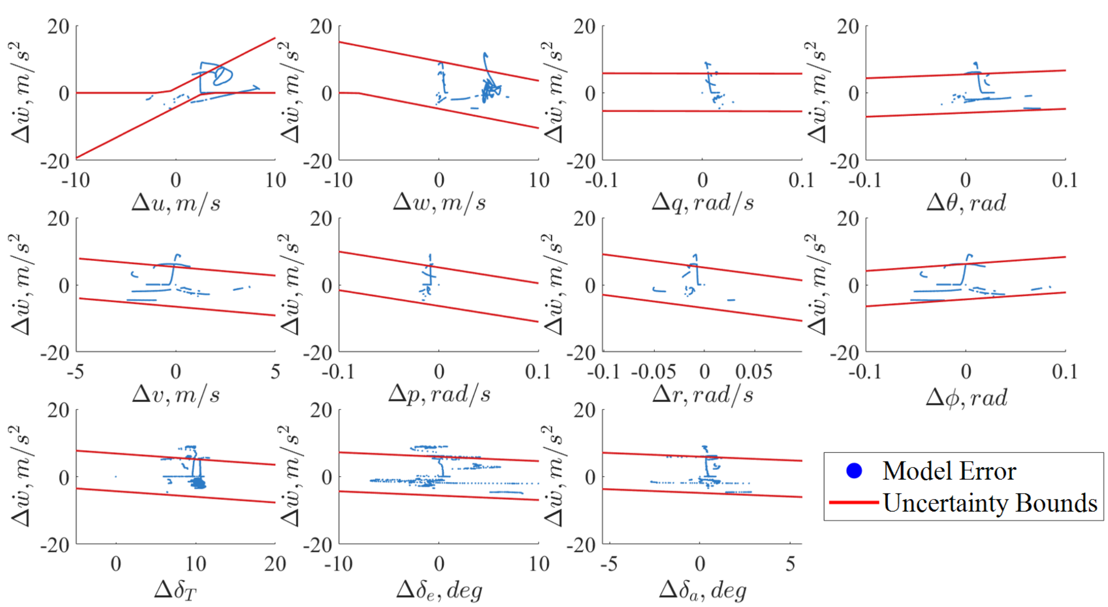

Figure 4.13: Calculated uncertainty bounds (red) and model form error (blue) for the tuned X-57 model, for the $\Delta\dot{w}$ state, corresponding to vertical acceleration.

4.5.4 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, which include 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.

4.5.5 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. 4.14, 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. 4.15. 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.

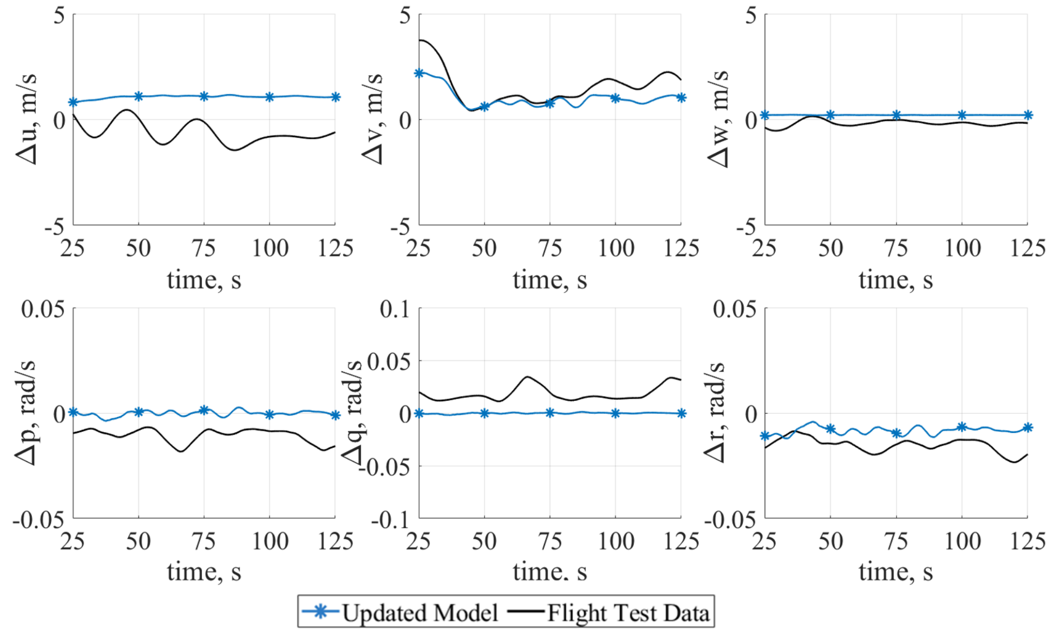

Figure 4.14: Comparison of the Mod-I tuned model (blue) to Tecnam P2006T flight test data, showing agreement between the two.

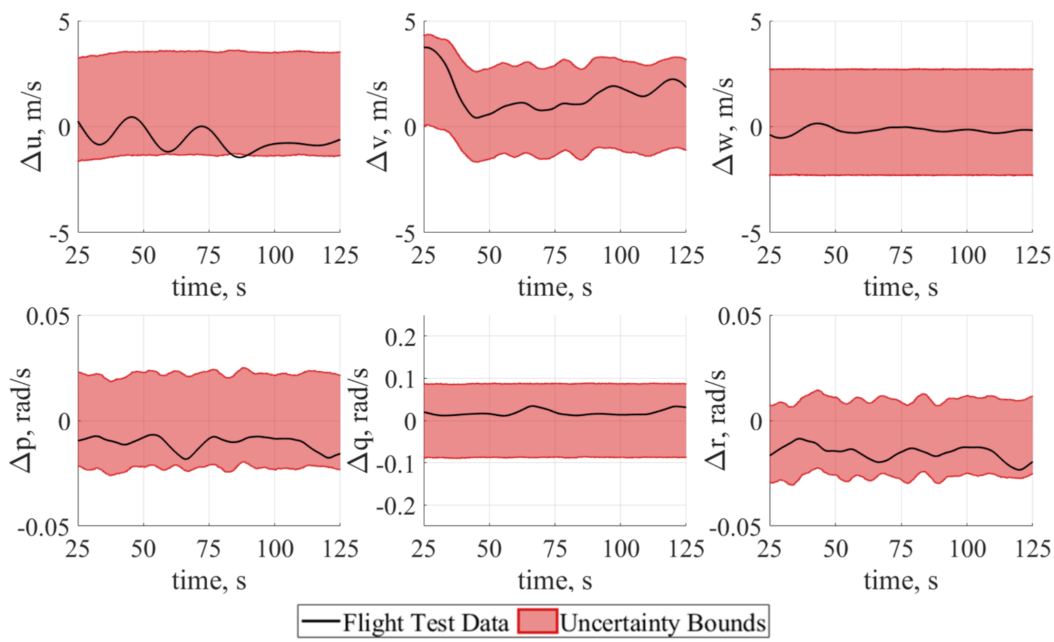

Figure 4.15: Uncertainty bounds (red) from non-deterministic simulation for the X-57 Maxwell Mod-I configuration, containing almost all of the Tecnam P2006T flight test segment.

4.5.6 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. 4.16, 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 $\delta C_{*}^{base}|_{modII}$, indicates that the Tuned Model Method, described in section 4.3.5 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. 4.17. 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.

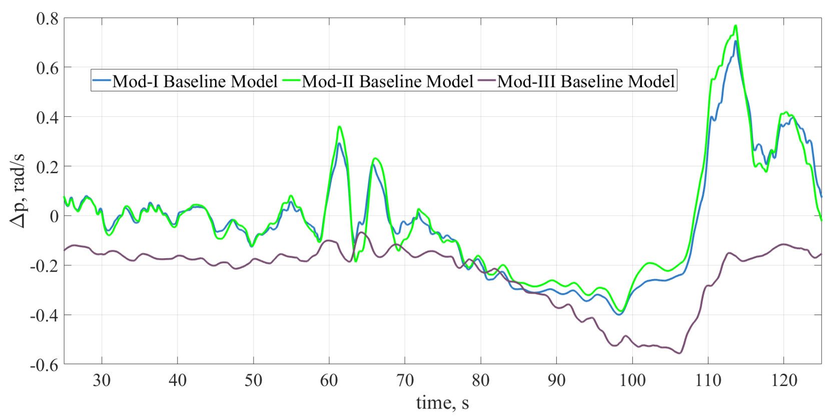

Figure 4.16: Comparison of a simulation the baseline model for the Mod-I configuration (blue), the baseline model for the Mod-II configuration (green), and baseline model for the Mod-III configuration (orange), demonstrating the differences between the three configurations.

Figure 4.16 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. 4.18 and is remarkably similar to the predicted performance for the Mod-II configuration.

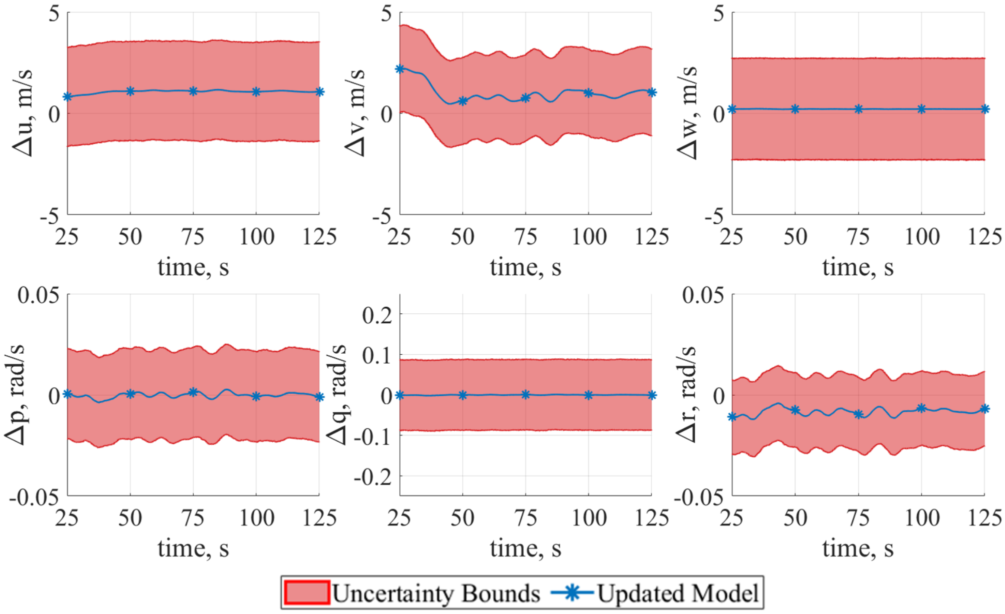

Figure 4.17: Updated model, indicated by stars, and the associated uncertainty bounds, for the X-57 Maxwell Mod-II Configuration, illustrating the predicted performance.

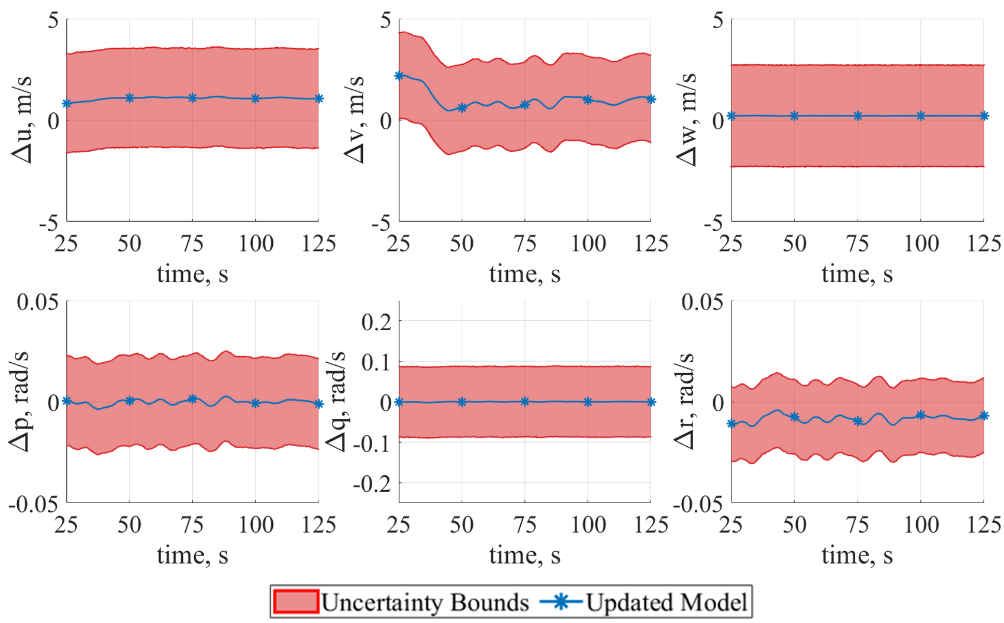

Figure 4.18: Updated model, indicated by stars, and the associated uncertainty bounds, in red, for the X-57 Maxwell Mod-III configuration, illustrating the predicted performance. Note the similarity to the estimate for the Mod-II configuration.

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.

4.5.7 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 23 CFR Part 2120; however, other airworthiness and handling criteria can be evaluated.

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 4.19 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. 4.19, 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.

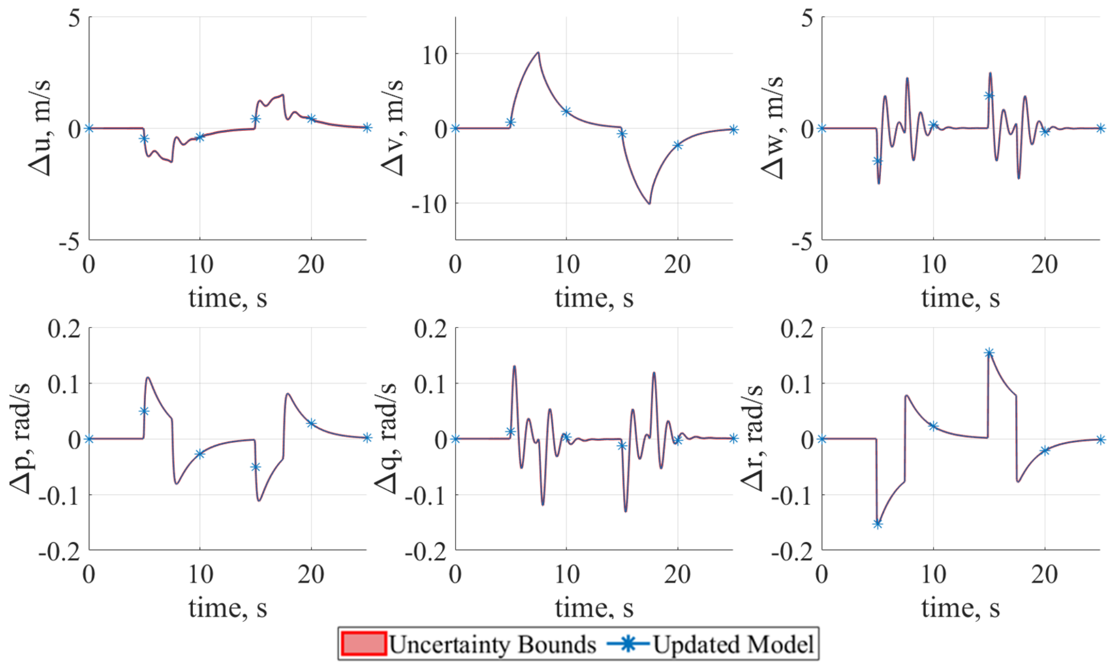

Figure 4.19: Prediction of X-57 Mod-II response to full aileron inputs, with maximum positive aileron at 5 seconds and maximum negative aileron at 15 seconds, showing adequate handling qualities for a normal category aircraft.

4.6 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 generated 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.

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 and John Leonard of NAVAIR 4.3.2.4 (Flight Dynamics), Theresa Shafer of NAVAIR 4.3.2.1 (Advanced Aerodynamics) and Andrew Pontzer of NAVAIR 5.1.2.15 (UAS) branches. 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.

Bibliography

[1] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, March 2010.

[2] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commercial Derivative Aircraft Acquisitions," Masters thesis, Knoxville, TN, May 2003.

[3] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2021. 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, URL http://arc.aiaa.org/doi/10.2514/6.2016-3920.

[5] American Institute of Aeronautics and Astronautics (ed.), *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, January 2021. doi:10.2514/4.106231.001, URL https://arc.aiaa.org/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, URL https://arc.aiaa.org/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, URL http://www.nap.edu/catalog/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, URL http://www.dl.begellhouse.com/journals/52034eb04b657aea,43e225911b944538,340d23ed5c6d1633.html.

[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, URL https://arc.aiaa.org/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, URL https://linkinghub.elsevier.com/retrieve/pii/S0045782511001290.

[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, URL https://arc.aiaa.org/doi/10.2514/6.2018-1762.

[12] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Rules and Standards Review," , September 2019.

[13] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Coordination Roadmap," , September 2019.

[14] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Gap Analysis," , September 2019.

[15] Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2nd ed., No. 245 in Progress in Astronautics and Aeronautics, AIAA, American Institute of Aeronautics and Astronautics, Reston, VA, June 2015.

[16] 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, Dallas, TX, June 2015. doi:10.2514/6.2015-2329, URL http://arc.aiaa.org/doi/10.2514/6.2015-2329.

[17] Montgomery, D. C., *Design and Analysis of Experiments*, eighth ed., John Wiley & Sons, Inc, Hoboken, NJ, 2013.

[18] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-3698.

[19] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-0274.

[20] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-2855.

Chapter 5

Summary and Concluding Remarks

Chapter 2 introduces a framework developed to estimate the performance and associated uncertainty of modified aircraft configurations. Two methods to estimate the performance and associated uncertainty bounds for modified aircraft configurations without requiring flight test or other high fidelity data of the modified configuration are introduced. The first uncertainty estimation method assumes that the model tuning for the nominal configuration is still valid for the modified configuration and that no additional uncertainty is introduced. The second method does not use the model tuning and thus develops the model using the lower fidelity data and associated larger uncertainty bounds in order to capture more of the modification dynamics. These methods are designed to be independent of the data collection method (wind tunnel, CFD, simulation, or flight test) as well as the model form (linear, non-linear) of the aircraft model.

These methods are then applied using data from the Generic Transport Model (GTM), a research aircraft operated by NASA Langley. A high fidelity simulation is used to create simulated flight test data as well as linearized models. Three modifications are examined, the addition of an equally distributed mass, the addition of a mass with a small change in aircraft center of gravity location, and the addition of a mass with a large change in aircraft center of gravity location. While the Tuned Model Method is suitable for predicting the performance of the equally distributed mass and small change in center of gravity modifications, the Baseline Model Method is unable to fully predict the performance for the large center of gravity configuration, indicating that the framework may not be suitable for this modification.

Chapter 3 then explores the effect of various requirements on this framework, focusing on the factors that affect the accuracy of the system identification and uncertainty quantification. The model form used to model the aircraft dynamics is shown to be important to correctly capturing the uncertainty and dynamics. The quality of the flight test data, including the noise levels and observed states, can also have a significant impact on the framework results. Other factors that affect the framework results include the amount of flight test data and the magnitude of the modification. Additional research into the applicability of each of the two methods, determining the range of acceptable modifications, is an area for future work and would require significant flight test data for a large spectrum of modified configurations.

Chapter 4 then applies this framework to the real-world example of NASA's X-57 Maxwell, a research aircraft designed with a series of modifications from a commercially available Tecnam P2006T aircraft to a fully electric aircraft with distributed electric propulsion. Both the Mod-II and Mod-III configurations have similar performance predictions to the nominal Mod-I configuration, a possible effect of the amount of sensor and wind noise present in the flight test data, or due to the design of the modifications. Because the modified aircraft has not yet flown, these predictions can be a useful comparison tool. Future work includes comparing these results to the flight test data for the Mod-II and Mod-III configurations when they become available.

This proposed framework is seen as an initial step towards certification by analysis. By including an estimation of uncertainty, certification criteria can be compared to a range of predicted performance as opposed to a single point estimate. Using this comparison enables stronger confidence in the results, potentially guiding areas where flight testing may be reduced or where additional flight testing may be needed. While this framework is still far from true certification by analysis, the hope is that this early step may help guide additional efforts, particularly with demonstrating means of compliance for simulation-based certification.

5.1 Future Work

Future work for this research includes additional research into the limitations of the applicability of the two methods, particularly establishing the range of acceptable modifications. Additional work is planned to complete the comparison of the framework results to the flight test data to the X-57 Mod-II and Mod-III configurations, when they become available, and to publish the results.

Bibliography

[1] Oberkampf, W. L., and Trucano, T. G., "Verification and Validation Benchmarks," SAND2007-0853, Albuquerque, NM, February 2007.

[2] Jordan, T., Langford, W., and Hill, J., "Airborne Subscale Transport Aircraft Research Testbed - Aircraft Model Development," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, AIAA 2005-6432, American Institute of Aeronautics and Astronautics, San Francisco, CA, August 2005. doi:10.2514/6.2005-6432, URL http://arc.aiaa.org/doi/10.2514/6.2005-6432.

[3] Oberkampf, W. L., and Roy, C. J., *Verification and Validation in Scientific Computing*, Cambridge Univ. Press, Cambridge, England, 2013.

[4] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-3698.

[5] "Flight Clearance Policy for Air Vehicles and Aircraft Systems," NAVARINST 13034.1D, Patuxent River, MD, March 2010.

[6] Lucka, D. A., "Refining the U.S. Navy Flight Clearance (Airworthiness Certification) Process: Maximizing Acquisition Reform Benefits for Commercial Derivative Aircraft Acquisitions," Masters thesis, Knoxville, TN, May 2003.

[7] *Standard Airworthiness Certification Regulations*, Federal Aviation Administration, Washington, D.C., 2021. URL https://www.ecfr.gov/.

[8] American Institute of Aeronautics and Astronautics (ed.), *Recommended Practice: When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification*, AIAA R-154-2021, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, January 2021. doi:10.2514/4.106231.001, URL https://arc.aiaa.org/doi/10.2514/4.106231.001.

[9] 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, URL https://arc.aiaa.org/doi/10.2514/6.2020-1520.

[10] *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, URL http://www.nap.edu/catalog/12531.

[11] Mehta, U. B., Eklund, D. R., Romero, V. J., Pearce, J. A., and Keim, N. S., "Simulation Credibilty - Advances in Vertification, Validation, and Uncertainty Quantification," NASA TP-2016-219422, November 2016.

[12] 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, URL https://linkinghub.elsevier.com/retrieve/pii/S0045782511001290.

[13] 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, URL http://www.dl.begellhouse.com/journals/52034eb04b657aea,43e225911b944538,340d23ed5c6d1633.html.

[14] 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, URL https://arc.aiaa.org/doi/10.2514/6.2001-1645.

[15] Oberkampf, W. L., DeLand, S. M., Rutherford, B. M., Diegert, K. V., and Alvin, K. F., "Error and Uncertainty in Modeling and Simulation," *Reliability Engineering & System Safety*, Vol. 75, No. 3, March 2002, pp. 333–357. doi:10.1016/S0951-8320(01)00120-X, URL https://linkinghub.elsevier.com/retrieve/pii/S095183200100120X.

[16] Schaefer, J. A., Cary, A. W., Duque, E. P., and Lawrence, S., "Application of a CFD Uncertainty Quantification Framework for Industrial-Scale Aerodynamic Analysis," *AIAA Scitech 2019 Forum*, AIAA 2019-1492, American Institute of Aeronautics and Astronautics, San Diego, CA, Janary 2019. doi:10.2514/6.2019-1492, URL https://arc.aiaa.org/doi/10.2514/6.2019-1492.

[17] Wendorff, A. D., Alonso, J. J., and Bieniawski, S. R., "A Multi-Fidelity Approach to Quantification of Uncertainty in Stability and Control Databases for use in Stochastic Aircraft Simulations," *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2015-3439, American Institute of Aeronautics and Astronautics, Dallas, TX, June 2015. doi:10.2514/6.2015-3439, URL http://arc.aiaa.org/doi/10.2514/6.2015-3439.

[18] Fidkowski, K., Kroo, I., Willcox, K., and Engelson, F., "Stochastic Gust Analysis Techniques for Aircraft Conceptual Design," *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA 2008-5848, American Institute of Aeronautics and Astronautics, Victoria, British Columbia, Canada, September 2008. doi:10.2514/6.2008-5848, URL http://arc.aiaa.org/doi/10.2514/6.2008-5848.

[19] Ng, L. W. T., and Willcox, K. E., "Monte Carlo Information-Reuse Approach to Aircraft Conceptual Design Optimization Under Uncertainty," *Journal of Aircraft*, Vol. 53, No. 2, March 2016, pp. 427–438. doi:10.2514/1.C033352, URL http://arc.aiaa.org/doi/10.2514/1.C033352.

[20] Kramer, B., Peherstorfer, B., and Willcox, K., "Feedback Control for Systems with Uncertain Parameters Using Online-Adaptive Reduced Models," *SIAM Journal on Applied Dynamical Systems*, Vol. 16, No. 3, January 2017, pp. 1563–1586. doi:10.1137/16M1088958, URL https://epubs.siam.org/doi/10.1137/16M1088958.

[21] Steinkellner, S., "Aircraft Vehicle Systems Modeling and Simulation under Uncertainty," Master's thesis, Linköping University Institute of Technology, Linköping, Sweden, 2011. URL http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-68068.

[22] 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, Dallas, TX, June 2015. doi: 10.2514/6.2015-2329, URL http://arc.aiaa.org/doi/10.2514/6.2015-2329.

[23] Hale, L. E., Patil, M., and Roy, C. J., "Aerodynamic Parameter Identification and Uncertainty Quantification for Small Unmanned Aircraft," *AIAA Guidance, Navigation, and Control Conference*, AIAA 2015-1538, American Institute of Aeronautics and Astronautics, Kissimmee, FL, January 2015. doi:10.2514/6.2015-1538, URL http://arc.aiaa.org/doi/10.2514/6.2015-1538.

[24] Maine, R. E., and Iliff, K. W., "The Theory and Practice of Estimating the Accuracy of Dynamic Flight-Determined Coefficients," NASA RP-1077, July 1981.

[25] Stripling, H., Adams, M., McClarren, R., and Mallick, B., "The Method of Manufactured Universes for Validating Uncertainty Quantification Methods," *Reliability Engineering & System Safety*, Vol. 96, No. 9, September 2011, pp. 1242–1256. doi: 10.1016/j.ress.2010.11.012, URL https://linkinghub.elsevier.com/retrieve/pii/S0951832011000755.

[26] Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2nd ed., No. 245 in Progress in Astronautics and Aeronautics, AIAA, American Institute of Aeronautics and Astronautics, Reston, VA, June 2015.

[27] Montgomery, D. C., *Design and Analysis of Experiments*, eighth ed., John Wiley & Sons, Inc, Hoboken, NJ, 2013.

[28] Denham, C. L., Patil, M., Roy, C. J., and Alexandrov, N., "Applicability of a Framework for Modeling Modified Aircraft Configurations Using Uncertainty," *AIAA Aviation 2021 Forum*, AIAA 2021-2793, American Institute of Aeronautics and Astronautics, Virtual, August 2021. doi:10.2514/6.2021-2793, URL https://arc.aiaa.org/doi/10.2514/6.2021-2793.

[29] 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, URL https://arc.aiaa.org/doi/10.2514/6.2018-1762.

[30] Jordan, T., Langford, W., Belcastro, C., Foster, J., Shah, G., Howland, G., and Kidd, R., "Development of a Dynamically Scaled Generic Transport Model Testbed for Flight Research Experiments," *AUVSI Unmanned Unlimited*, 2004.

[31] Murch, A., and Foster, J., "Recent NASA Research on Aerodynamic Modeling of Post-Stall and Spin Dynamics of Large Transport Airplanes," *45th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 2007-463, American Institute of Aeronautics and Astronautics, Reno, NV, January 2007. doi:10.2514/6.2007-463, URL http://arc.aiaa.org/doi/10.2514/6.2007-463.

[32] Cunningham, K., Cox, D., Murri, D., and Riddick, S., "A Piloted Evaluation of Damage Accommodating Flight Control Using a Remotely Piloted Vehicle," *AIAA Guidance, Navigation, and Control Conference*, AIAA 2011-6451, American Institute of Aeronautics and Astronautics, Portland, OR, August 2011. doi:10.2514/6.2011-6451, URL http://arc.aiaa.org/doi/10.2514/6.2011-6451.

[33] 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, URL http://arc.aiaa.org/doi/10.2514/6.2016-3920.

[34] *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, URL http://www.nap.edu/catalog/12531.

[35] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Rules and Standards Review," , September 2019.

[36] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Coordination Roadmap," , September 2019.

[37] Schlickenmaier, H., Voss, M. G., and Wilkinson, R. E., "Certification Gap Analysis," , September 2019.

[38] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-0274.

[39] 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, URL https://arc.aiaa.org/doi/10.2514/6.2019-2855.