31st Congress of the International Council of the Aeronautical Sciences
Belo Horizonte, Brazil; September 09-14, 2018

UTILIZATION OF SCALING LAWS AND UNCERTAINTY QUANTIFICATION TO INFORM TECHNOLOGY DEVELOPMENT EXPERIMENTATION

Katherine G. Schwartz, Ph.D., Dimitri N. Mavris, Ph.D.
Georgia Institute of Technology

Keywords: *uncertainty quantification, wind tunnel testing, technology development*

Abstract

The technology and system development process involves planning and conducting a series of experiments that will result in a fully developed, fully mature entity. Experiments are defined by many attributes, and there is a need for a formal experiment design process that utilizes a systems engineering framework to ensure that clear requirements are defined and the selected attributes result in an experimental plan that meets those requirements. This research outlines a three-phased, systems engineering-based experiment design approach. Discussion on key enablers, such as scaling laws and similitudes, technology readiness assessments, and uncertainty quantification is provided and it is established how they would be included in the resulting approach. After the approach is outlined, a tailored discussion around wind tunnel testing is provided to reiterate how complex of a problem experiment design can be and demonstrate the need for this formalized approach.

Nomenclature

F	*forces, N*
ρ_f	*fluid density, kg/m^3*
μ	*absolute viscosity, N·sec/m^2*
Vs	*velocity of sound, m/sec*
a	*linear acceleration, m/sec^2*
δ	*control surface position, deg or rad*
Ω	*angular rate, rad/sec*
ω	*frequency of oscillation, rad/sec*
g	*acceleration of gravity, m/sec^2*
t	*time, sec*
m	*mass, kg*
I	*mass moment of inertia, kg·m^2*
EI'	*bending stiffness, N·cm^2*
GJ'	*torsional stiffness, N·cm^2*
l	*characteristic dimension, m*
C_L	*coefficient of lift*
q	*dynamic pressure, N/m^2*
Cm	*aerodynamic pitching moment*
M	*Mach number*
Re	*Reynolds number*
Fr	*Froude number*
St	*Strouhal number*
PSP	*pressure sensitive paint*
LDV	*laser dopler velocimetry*
DGV	*doppler global velocimetry*
PIV	*particle image velocimetry*

1 Introduction

As more aggressive performance goals are set for next generation aircraft systems, engineers are required to look at developing technologies to enable the design of these systems for the given requirements. Engineers are tasked with making the difficult decision of which technologies should be pursued and eventually integrated into the aircraft. A systems engineering approach can be utilized by engineers to decompose performance requirements into lower level metrics, or areas of desired improvement, that can be targeted by technologies. Technologies are then selected based upon their expected impact to the identified improvement areas. However, this decision is still difficult for engineers to make due to the low maturity of the technologies, which introduces uncertainty into their expected performance impact. Therefore, engineers need to be able to make a risk-informed decision about which technologies to pursue, and how to appropriately reduce the uncertainty surrounding their performance impacts.

Technology readiness progression, and the corresponding uncertainty reduction, is linked to planning and conducting sets of experiments throughout the development process. Planning appropriate experimentation that will lead to readiness progression requires the identification of key uncertainty sources at the lower level metrics that are driving the overall performance uncertainties. Once these uncertainty sources have been identified through sensitivity analyses or similar processes, they can be targeted through experimentation.

In general, development activities are planned to gain new information about the technologies in question. As new information is gained, it is expected that the readiness will increase and the uncertainty surrounding the performance will be reduced. There are many characteristics of an experiment that impact how useful the resulting experimental data can be with regards to maturing the entity it is testing. These characteristics include information regarding the test article, the test environment, and the types of measurements taken. While consideration of all these things may seem straightforward, making these decisions in a consistent manner that results in an experiment plan meeting all requirement is not trivial.

A process that allows for the selection, or optimization, of the appropriate experimental settings for a given set of requirements is desired. Formalization of this experiment planning process, starting with identification of requirements and going through the entire detailed planning, has been addressed in this research through a three-phased approach. The research presented herein builds upon past research on experiment design through analytical analysis and more closely focuses on the selection of the type of experiment based upon technology readiness requirements. This outlined method utilizes several key enablers, such as scaling laws and technology readiness definitions, to result in a set of experiments that have a high likelihood of meeting the defined experiment requirements throughout the development process. Lastly, a more detailed discussion on wind tunnel testing will be provided to reiterate why careful consideration of all experiment requirements is important and not trivial.

2 Systems Engineering Formulation

Identifying the appropriate experiment to perform during technology development can be difficult if the right experiment requirements are not identified and analyzed. It was recognized that the broader subject of requirements definition is well formulated in the area of systems engineering. In the generic systems engineering approach there are three main segments: requirements definition, requirements flowdown, and requirements allocation. In terms of a generic aircraft design process, these steps can be defined as:

- **Requirements definition:** Requirements are set from a variety of means. Requirements define the overall objective of the system in terms of performance, safety, etc.
- **Requirements flowdown:** The top level requirements are flowed down to define lower level requirements that can be mapped to systems, sub-systems, etc. The flowdown results in multiple potential scenarios or avenues that could be taken to meet the top level objectives.
- **Requirements allocation:** A specific scenario identified through the requirements flowdown step is selected to pursue. This scenario will be a series of design choices that enable the resulting system to meet the established top level requirements.

These three main systems engineering concepts were leveraged to identify the key aspects this experiment design formulation must encapsulate.

When formulating an experimental campaign, there must be a set of requirements that define the overall objective of the experiments to be performed. Requirements for the experimentation can be set through multiple avenues, including the identification of key uncertainty sources that need to be investigated, key demonstrations required for increase in readiness and/or certification, and key physical phenomena that must be further investigated or demonstrated. All of these considerations, including others that may arise, are important for defining the overall requirements of the experimental campaign. Failure to properly identify all potential requirements could result in an experimental campaign that does not provide the highest value and leads to a waste of time and resources.

Upon the completion of defining the requirements for the experimentation, potential experimental plans must be identified. The identification of the potential experimental solutions is analogous to the requirements flowdown portion of the systems engineering process. During this phase of the experiment design the type of phenomena that needs to be observed and the key disciplines that need to be captured are enumerated based upon the set requirements. Details such as the current level of understanding of the phenomena of interest and the availability of high fidelity simulation tools help determine if computer-based simulations are adequate or if physical experimentation is required. To properly represent each discipline, the different types of analyses/experimentation that are needed must be enumerated to adequately capture each discipline. Determining how to capture each discipline is an important issue for both computer-based simulations and physical experimentation. If physical experimentation is pursued, more considerations exist, such as the proper experimental facility, the test article, the measurement devices, etc.

Through the requirements flowdown step of the systems engineering process, the different potential experimental options will be enumerated. This will result in a set of alternatives that engineers can select from to establish the final experiment design. The process of selecting an experimental approach is analogous to the requirements allocation step of the systems engineering process. The selection of key experiment characteristics, such as test facility and test article scale, represent the allocation of a requirement, or set of requirements, to a specific experimental detail, or set of details. As long as all of the defined experiment requirements are properly allocated throughout the decision making process, the final experiment should be able to meet the defined objectives and requirements.

As explained, the systems engineering process provided the framework for defining the experiment design methodology formulated through this research. Requirements definition, requirements flowdown, and requirements allocation are important steps to consider in any design problem, including the design of an experimental plan. The following section will formalize the approach and establish some of the key tools and enablers that will be vital to each step of the process.

3 Approach and Key Enablers

Following the systems engineering narrative previously established (requirements definition, requirements flowdown, and requirements allocation), a three-phase experiment design philosophy was established. The three phases of experimentation are defined as:

- Thought Experiment Formulation
- Detailed Experimental Design
- Design of Experiments Definition

3.1 Thought Experiment Formulation

3.1.1 Overview of Step

Thought experiment formulation is the first phase of the experiment planning formulation proposed herein. During this phase, the main purpose(s) of the experiment is defined and decomposed into experimental requirements. Key aspects of the experiment that are addressed during this phase include the phenomena and key disciplines that must be captured, the type of experiment (physical, numerical, ground, flight, etc.), and the desired level of fidelity of the experiment.

As previously discussed, there are many different potential experiment purposes and several different types of information that could be consulted to help define the appropriate experiment purpose. It has been observed both through literature and through direct experience on technology development programs that experiment requirements are defined through the following means: technology readiness assessments, uncertainty analysis, and certification standards. Previous work from the authors has investigated the synthesis of information from technology readiness assessments and uncertainty analysis for the purpose of planning technology development experimentation.[1]–[3] The following sub-sections provide relevant background information on these key enabling concepts as they pertain to the experiment design process.

3.1.2 Technology Readiness and Uncertainty Reduction

The Technology Readiness Level (TRL) scale is the current state of the art for tracking technology readiness. TRL was established in 1995 by Mankins and is formally described as a ``systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technologies".[4]

As a technology progresses through its development process, it graduates from one TRL level to the next. There is, however, question about how a given experimental plan is deemed adequate to validate TRL graduation. The characteristics that define an experiment can be decomposed and mapped to the established attributes of the TRL in question.

The wide usage of TRL implies it is a well-established metric for readiness communication. The TRL metric, and the definitions provided for each level of the TRL scale, can be decomposed into a set of attributes that TRL tracks. In previous research the authors have done a full decomposition of the TRL scale [5]. When defined and synthesized, these attributes of readiness create the overall TRL measure. The attributes include aspects of the test environment, the entity being tested, and the overall purpose of the TRL level.

The first two attributes address the test environment. The test environment attributes are the type of test environment and the fidelity of the test environment. In this context, fidelity is a measure of realism. Example options for the type of test environment: computer simulated, lab, or real-world. The fidelity of the test environment is defined by the number of assumptions taken and how close the environment is to the intended operating environment. In these environments simplifying assumptions are utilized to either isolate a condition or phenomenon. An issue that may arise is the separation between the two options.

The remaining three attributes define the test article. The first attribute is the fidelity of the test article and it is divided into four options: a non-physical model, a prototype with non-working parts, a prototype with working types, and actual hardware. Similarly to the test environment relevance, it may seem difficult to determine the separation between these two options. The scale of the test article is simply divided into two options: sub-scale and full scale. Sub-scale is any size that is not the anticipated size of the final article. Throughout most of development the test articles will be sub-scale, until the final phases. It is acknowledged that there are an infinite number of scales that can be defined as sub-scale. If a technology development program wishes to divide sub-scale into multiple options or specific sizes, the morphological analysis can be altered. The final attribute is the level of the test article. In this context, level refers to the level of the system that is being modeled. Level can also be referred to as the number of integrated parts being modeled.

Defining experimentation based upon the TRL metric is a start to ensuring that TRL graduation can be achieved. However, TRL graduation can also be linked to the amount of performance uncertainty that is reduced over time by gathering new data and information. The ability to quantify and track uncertainty can assist in system risk analysis and provide decision makers with valuable trade-off information that would otherwise be unavailable or unknown. Therefore, it is important to follow well-defined, mathematically based procedures for the identification, assessment, and treatment of uncertainty sources. There are many sources of uncertainty in system design and development, and there is a need for a sound taxonomy to categorize the types according to the fundamental essence of the sources and how they affect the system.[6] In the literature there are several different taxonomies used by different science and engineering disciplines.[7] It is observed that the terms epistemic uncertainty and aleatory uncertainty are very prevalent in the uncertainty community, and their definitions have generally been agreed upon. The concept of characterizing uncertainties as either reducible or irreducible is important during the experimentation planning phase of technology development, which is one reason why the separation of uncertainty sources as either aleatory or epistemic was deemed desirable. In this context, aleatory uncertainty is considered irreducible and the definition of is consistent with the definition previously presented, which is the inherent or natural variation of a measured quantity.[6], [8]–[10] Epistemic uncertainty is uncertainty due to incomplete knowledge.[6], [9], [10] It is considered reducible because it can be reduced and potentially

Based on this definition of uncertainties, it is desirable to be able to identify epistemic uncertainty sources so experiments can potentially be planned to reduce them. Identification of epistemic uncertainty sources, and quantifying their overall impact on the system performance, can be done through uncertainty quantification techniques.

After uncertainty sources are characterized, their effects on other parts of the system under consideration can be determined through uncertainty propagation and further analysis. It can be important to decision makers to determine the value of reducing certain sources of uncertainty over others, and further, determine what type of information is needed to provide that value.[11] One such analysis method to facilitate this is sensitivity analysis, where the goal of is to apportion the uncertainty in a given output to the uncertainty in each of the inputs.[12] It is a technique that provides engineers with the ability to determine if a model resembles the system it represents, the factors that contribute to the output variability the most, parts of the model that are insignificant, optimal regions within the simulation space, and interactions among factors.[11][13]

After uncertainty has been analyzed, it can then be reduced. Uncertainty reduction is facilitated by gaining new knowledge about the entity in question, which can be achieved via planning experimentation to gather new data. The uncertainty analysis results can be used to determine the type of information, or the type of experimentation, that will provide uncertainty reduction. Some approaches currently exist in the literature that utilize uncertainty quantification results for experiment planning and prioritization.[14]–[16] These approaches aim to use the information to prioritize either identified technology uncertainty sources or experiments within a set of proposed development activities. Prioritization of technology uncertainty sources is completed by comparing the existing amount of uncertainty linked to each technology impact or comparing how the uncertain technology impacts affect the system level objectives. The latter prioritization method is enabled by sensitivity analyses. Prioritization of proposed experiments is completed by comparing the impact the experiments are expected to have on either the amount of input uncertainty or the amount of uncertainty surrounding the system objectives. This requires estimates of the amount of expected uncertainty reduction an experiment can provide.

3.2 Detailed Experimental Design

3.2.1 Overview of Step

The second phase of the experiment design process is the Detailed Experiment Design phase. During this phase the requirements and purpose of the experiment previously defined are utilized to aid in the selection of the experiment details. Making these decisions first requires the enumeration of all of the potential experiment options. These options include the type of test article, the scale of the test article, the experimental facility, the sensors that will be used to collect data, etc.

Once the different options are available, engineers will then use the requirements of the experiment, as well as available resources, to aid a down-selection process. The result of this phase of design will be all practical details of the experimental set-up, leaving only the detailed definition of the test matrix to be completed.

There are several key concepts that aid the detailed experiment design process. The first of which is a method called morphological analysis, which enables a systematic and organized process for enumerating and organizing all available experiment design options. The second key enabler is the field of scaling laws and similitudes, which helps create and maintain a desired level of fidelity for the phenomena being tested. Details on these two enablers are provided in the next two sub-sections.

3.2.2 Morphological Analysis

Morphological analysis is a method that traces back to the 13th century and was formalized in 1942 by Swiss astronomer Zwicky. The basic idea behind morphological analysis is to break down the subject under investigation into a number of fundamental dimensions that completely describe the subject. Wissema concludes that an early example of morphological analysis can be found in Mendeleyev's periodic table of elements because the arranged the elements in the table according to the many different properties that define them.[17] The process of morphological analysis consists of five main steps. The first step is to identify the different dimensions, or functions, of the subject under investigation. The second step is to identify the different ways each dimension can manifest itself. Next, all of the potential combinations represented by the different dimensions choices are calculated. The final two steps involve identifying the practical combinations and then reducing this set even further to choose a final combination.

Morphological analysis has been used in many disciplines, including aircraft design and technology development. Several researchers have utilized morphological analysis for technology forecasting.[17]–[20] Wissema concluded with his research that morphological analysis provides a good systematic starting point for a technology forecasting framework or investigation, but ultimately should be supplemented with other methods. He also notes that morphological analysis may be confusing at the beginning of problem formulation, but will be come clearer as more is understood about the subject. Morphological analysis has been utilized in the literature to decompose the aircraft system into different sub-systems and components and then identify different potential vehicle architectures. This concept works very well to enumerate the different aircraft integration concepts and book keep the system assumptions during technology development.

3.2.3 Scaling Laws and Similitudes

There are many characteristics of an experiment once it is defined that impact how useful the resulting experimental data can be with regards to maturing the entity it is testing. As previously mentioned, these characteristics include information regarding the test article, the test environment, and the types of measurements taken. With regards to the test article, it can be defined by its level of integration (component, subsystem, etc.), functionality, and its scale. Furthermore, the testing conditions must be scaled appropriately in addition to the test article. Selection of the appropriate test article scale and the testing conditions are experiment details that are very important and decisions that are subject to many constraints. These constraints include the application of scaling laws, or similitudes, that must be considered to ensure the physics engineers desire to capture and define through the test data is not altered or misunderstood.

Scaling laws are provided in the form of non-dimensional numbers that are created by going through the process of dimensional analysis. Dimensional analysis is the process of decomposing relationships between physical quantities and their units of measure to create new non-dimensional relationships that can be utilized for comparisons of different scenarios. For a given experiment, the scaling laws that are important to maintain depend on the physics that the experiment is aiming to capture and the disciplines that are relevant to the phenomena. In general, it is not expected that a single test article will meet all possible similitudes because experiments are designed for a primary purpose, especially in early development stages. However, designing an experiment with a test article that meets as many similitudes as possible can lead to a set of data that can be utilized for a wider range of purposes. This includes a greater ability to calibrate and validate modeling environments, ability to reduce more performance uncertainty at the technology and system level, and a greater overall understand of the physics of the design problem at hand.

For an aircraft, the forces and moments are a function of the geometry, kinematics, aerodynamics of the aircraft, properties of the fluid, accelerations and velocities, and displacement. This functionality is summarized in the below equations for forces (F) and moments (M).

(1) $$F = f(\rho_f, \mu, V_s, l, \alpha', a, \delta, \Omega, \dot{\Omega}, \omega, g, t, m, I, EI', GJ')$$

(2) $$M' = f(\rho_f, \mu, V_s, l, \alpha', a, \delta, \Omega, \dot{\Omega}, \omega, g, t, m, I, EI', GJ')$$

Through dimensional analysis, the force and moment equations can be non-dimensionalized and become a function of the non-dimensional parameters provided in the next equations provided below:

(3) $$\frac{F}{(\frac{1}{2})\rho_f V^2 l^2} = f\left(\begin{matrix} \alpha', \delta, \frac{\Omega l}{V}, \frac{\dot{\Omega} l^2}{V^2}, \frac{al}{V^2}, \frac{\omega l}{V}, \\ \frac{\rho_f V L}{\mu}, \frac{V^2}{lg}, \frac{V}{V_s}, \frac{m}{\rho_f l^3}, \frac{I}{\rho_f l^5}, \\ \frac{EI'}{\rho_f V^2 l^4}, \frac{GJ'}{\rho_f V^2 l^4}, \frac{tV}{l}) \end{matrix}\right)$$

(4) $$\frac{M\prime}{(\frac{1}{2})\rho_f V^2 l^3} = f\left(\begin{matrix} \alpha', \delta, \frac{\Omega l}{V}, \frac{\dot{\Omega} l^2}{V^2}, \frac{al}{V^2}, \frac{\omega l}{V}, \\ \frac{\rho_f V L}{\mu}, \frac{V^2}{lg}, \frac{V}{V_s}, \frac{m}{\rho_f l^3}, \frac{I}{\rho_f l^5}, \\ \frac{EI'}{\rho_f V^2 l^4}, \frac{GJ'}{\rho_f V^2 l^4}, \frac{tV}{l} \end{matrix}\right)$$

Further implementation of the dimensional analysis process leads to the equations of motion that are utilized in aircraft analysis. Examples of the equations of motion for an aircraft in a dimensionless form are provided by the following equations for lift coefficient (C_L) and moment coefficient (C_M).

(5) $$C_L = \frac{m(\ddot{z}+qV+g)}{\bar{q}S} = C_{L_u}\frac{\Delta u}{V} + C_{L_\alpha}\Delta\alpha + C_{L_q}\frac{q\bar{c}}{2V} + C_{L_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{2V} + C_{L_{\delta_e}}\delta_e + C_{L_{\dot{\delta}_e}}\frac{\dot{\delta}_e\bar{c}}{2V}$$

(6) $$C_m = \frac{I_y\dot{q}}{\bar{q}S\bar{c}} = C_{m_0} + C_{m_u}\frac{\Delta u}{V} + C_{m_\alpha}\Delta\alpha + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{2V} + C_{m_{\delta_e}}\delta_e + C_{m_{\dot{\delta}_e}}\frac{\dot{\delta}_e\bar{c}}{2V}$$

The equations for C_L and C_m are used to analyze the performance of an aircraft; however, there are other factors that are used in the experiment design process. In the field of aerodynamics, there are several similtudes that are commonly investigated, including: angle of attack, geometric parameters, Mach number, Froude number, Strouhal number, and Reynolds number. These similutudes are generally a function of the following key physical properties:

- Pertinent properties of fluid: mass density ρ_f, absolute viscosity μ, speed of sound V_s
- Aircraft geometry: mass *m*, inertia *I*, elastic bending and torsional rigidity (*EI*, *GJ*)

A full enumeration of similitude parameters relevant to aircraft analysis are provided in NASA Technical Paper 1435 (NASATP 1435) titled "*Similitude Requirements and Scaling Relationships as Applied to Model Testing*" by Wolowicz, Bowman, and Gilbert. [21] Details of some of the pertinent similitudes are provided below:

- Reynolds number (Re)
  - Ratio of the fluid's inertial forces to the viscous forces in the boundary layer of the fluid
  - Important for comparing the dynamic similarity of the flow around test articles
  - A mismatch of Reynolds numbers implies the two scenarios are not dynamically similar
- Mach number (M)
  - The ratio of an article's velocity to the speed of sound of the fluid medium
  - Matching of this parameter ensures fluid compressibility effects on the article are considered
- Strouhal Number (St)
  - Utilized to establish similitude for unsteady flow effects caused by oscillatory perturbations of the article
- Froude Number (Fr)

- Utilized to establish similitude of inertial and gravitational effects on maneuvering articles

3.3 Design of Experiment Definition

3.3.1 Overview of Step

The final phase of the experiment design process is to set the test matrix for the experimental campaign, which will be referred to as the Design of Experiments definition phase. Meticulously creating a test matrix that will provide the maximum amount of information is an important final step of experiment planning. A test matrix is created by enumerating the different independent variables that will be varied in the experiment and the ranges of interest for each. Once the ranges have been created, they can be discretized to create individual settings for each independent variable.

If there were no time and resource constraints for an experimental campaign, a full factorial test matrix could be utilized; however, this is rarely, if ever, the case. Therefore, a reduced-size test matrix must be comprised. Therefore, those in charge of experiment design must determine the number of cases or trials that can be performed and how those cases should be defined. There exists a technique that has been utilized across many disciplines, including aerospace engineering, that can aid this step of experimental design. This technique is referred to as Design of Experiments (DOE) and is further described in the following sub-section.

3.3.2 Design of Experiment

Design of Experiments (DOE) refers to a set of cases, runs, or trials for a given experiment or simulation that is designed to maximize information and minimize experimental effort. The concept of DOE originated in the 1920s in the agricultural field when statistician R.A. Fisher could not make statistically sensible conclusions for crop yield prediction despite decades of information on temperature, rainfall, and other factors. Fisher standardized the process of experimental design to give structure to the process, and the techniques have been refined over the years by Yule, Box, Hunter, Scheffe, Cox, and others.

The DOE techniques were popularized by Genichi Taguchi in the field of manufacturing in the 1960s. There are several key concepts that are considered when constructing DOEs. Some of these are as follows:

- Replication: this refers to repeating trials or measurements and is useful if the results have inherent noise. Replication is not typically used in simulation
- Correlation: this implies a non-independence of input variables and must be considered while constructing DOEs
- Orthogonality: implies zero correlation between experimental factors. A purely orthogonal design is used to maintain the independence of independent variables.
- Blocking: arranging experimental units into groups that are similar to one another to reduce known but irrelevant sources of variability and focus on the estimation of study parameters
- Factorial design: allows the effect of several factors and their interactions to be determined with the same number of trials as are needed to determine any single effect. Factorial designs are used in place of one-variable-at-a-time studies

There are four general types of uses for DOE. They first is comparative, where the engineer is interested in assessing whether a change in a single factor has resulted in a change/improvement to the process as a whole. The second is for screening or characterization, where the engineer is interested in "understanding" the process as a whole in the sense that he/she wishes (after design and analysis) to have in hand a ranked list of most important to least important that affect the process. The first is for modeling, where the engineer is interested in functionally modeling the process with the output being a good-fitting (high predictive power) mathematical function, and to have good (maximal accuracy) estimates of the coefficients in that function. The last use is for optimization, where the engineer is interested in determining optimal settings of the process factors.

4 Case Study

The experiment design process described in the previous sections can apply to all systems and/or technologies under development and help guide experimentation efforts for all disciplines of study. To reiterate, the motivation of this process is to ensure that the right experiments are being performed for the given amount of time and resources available.

To provide further discussion, an example focusing on experimental efforts for aerodynamic characterization of a developing aircraft concept has been provided. This example focuses on the NASA developed Common Research Model (CRM) and one of its previous experimental campaigns. The proceeding sections will provide some relevant background information on the CRM, and discussion on each of the three phases of the outlined approach for the selected experimental campaign.

4.1 NASA Common Research Model Overview

The NASA Common Research Model is an open source model developed by NASA with the intent of being a baseline reference for conducting experiments using wind tunnels and as a source for verification and validation of CFD results across the industry. The model started as a paper study through collaboration with both government and industry and has since evolved into the creation of physical test articles for wind tunnel testing purposes. The idea for the CRM came because of a series of Drag Prediction Workshops where the need for a publicly available dataset of a state of the art transport aircraft geometry that could be utilized for computational fluid dynamics (CFD) validation was identified. The types of measurements that were identified as important for this dataset to contain were force and moment measurements, pressure distributions, skin friction measurements, off-body flow field mesuarements, and unsteady data. Configuration definition for the CRM was intiated in 2007 by NASA with input from aerodynamic leaders in the US and specific support from Boeing engineers in detailed aerodynamic design through 2008. Wind tunnel model design and fabrication followed by wind tunnel testing. Initial tests of the configuration were funded by NASA Fundamental Aeronautics Subsonic Fixed Wing program. Detailed information on the geometric definition of the CRM are publicly available through a NASA-run website.

Numerous papers have been published using the NASA CRM to compare generated CFD results against experimental data and other published CFD data. The models are available online to download along with the experimental test data that has been collected. The experimental test data includes data collected from the National Transonic Facility, the Ames 11ft Wind Tunnel, and the European Transonic Wind Tunnel[22]–[24]. The NASA CRM has also been tested by the Japanese Space Agency [25]–[27]. Specific measurements included in these data sets are aerodynamic forces and moments, pressures measured using pressure taps and pressure sensitive paint, skin friction, model deformation under load, and off-body velocity measurements measured using particle image velocimetry. The NASA CRM model has been used in the fourth, fifth, and sixth AIAA drag prediction workshops [28], [29].

Due to the nature of the CRM program, details of the experimental campaigns as well as the test data is publicly available. For further discussion, two experimental campaigns will be utilized in the remaining sub-sections. These two campaigns are the first two conducted for the CRM in 2010. The first experimental campaign was conducted in the NASA Langley National Transonic Facility (NTF) and the second was conducted in the NASA Ames Transonic Wind Tunnel (TWT).

4.2 Test Case Thought Experiment Design

Wind tunnel testing is conducted for a variety of reasons, including characterizing the aerodynamic performance of a system (propeller, airfoil, wing planform, fuselage, aircraft system, inlet, etc.), aeroelasticity characteristics, propulsion airframe interactions, aeroacoustics, and others. Furthermore, wind tunnel data helps create aerodynamic databases that can be utilized for modeling and simulation verification and validation, which helps reduce model form uncertainty and parameter uncertainty.

Many of the experimental requirements for the CRM originated from the AIAA Drag Prediction Workshops (DPW). The AIAA DPWs have been conducted every 2-4 years since the first DPW (DPW-I) in 2001. The purpose of the DPWs is to serve as a forum for determining the effectiveness of existing Navier-Stokes solvers and techniques [23]. Through the first three DPWs, experimental results from different publicly released vehicle configurations were utilized to validate the jointly-developed quantitative results. For the fourth DPW, DPW-IV, the CRM geometry was introduced and calculations were conducted on it in the absence of any experimental data for validation. Therefore, there was a desire by the community to produce experimental data on the CRM configuration for validation purposes of the DPW-IV calculations.

DPW-IV focused on performing calculations for three different cases. Case 1 was divided into two sets. The first was a grid-convergence study at M=0.85 and Re number of 5 million. The second was a downwash study at the same M and Re number conditions through a sweep of angels of attack. Case 2 was a Mach-Sweep study that ranged from Mach of 0.7 to a Mach of 0.87. The Re number was again at 5 million. Case 3 was a Reynolds number study where both 5 million and 20 million were investigated at Mach number 0.85. [26]

Specific uncertainty reduction targets were not set for the CRM, and it is not being developed for production purposes so traditional development progress (i.e. following the TRL progression) is not expected. However, the types of calculations performed at DPW-IV assisted in setting experimental requirements for the first CRM experimental campaigns performed in 2010. In general, the requirements for the initial CRM experiments were set by the need to capture basic data on a new geometry configuration with new, modern measurement capabilities and focusing on force/moment measurements including and beyond cruise drag.[28] These high level requirements were utilized to shape the type of models and testing conditions that were utilized for the first set of experiments. This will be described in greater detail in the following section.

4.3 Test Case Detailed Experimental Design

As outlined, the desire of the 2010 CRM experimental campaign was to conduct wind tunnel tests for the purpose of generating data for comparison with DPW-IV results. The NASA-CRM community was then tasked to design a set of experiments that would provide the required data for the validation efforts. There are many decisions that must be made to fully define a wind tunnel experimental setup. An exercise was conducted to define a list of attributes for a wind tunnel test that must be defined when designing a wind tunnel experiment. As described in Section 3.2, morphological analysis was utilized to aid the enumeration of such attributes.

The morphological analysis shown in Table 1 is not meant to be exhaustive; however, it is meant to demonstrate that there are many different attributes to determine and each attribute has a variety of choices. The attributes in general can be divided between the categories of wind tunnel characteristics, sensing characteristics, and test specimen characteristics. As previously mentioned, selection of all attributes is dependent on the requirements of the experimental campaign that are set during the first phase of the experiment design, the Thought Experiment Formulation. The first category shown in Table 1 is the overarching class, or purpose, of the experiments being planned. Listed are some options, such as aerodynamics, acoustic, and icing. A test could also have multiple classes.

The selection of the right wind tunnel at times is dependent on the wind tunnel availability. When multiple wind tunnels are available, they can be compared and contrasted by the attributes that define them, as shown in Table 1. Wind tunnels are defined by their test section characteristics and the testing conditions they can simulate among other details. Each wind tunnel has different test section sizes and can simulate different testing conditions, so the down-selection can be dependent on other experimental attributes that will be defined. For the test section itself, the size varies and a few examples are provided. The test section can be either open, closed, or reconfigurable. If the test section is closed, the walls or barriers that block it off from the rest of the tunnel can be slotted, solid, or porous.

Wind tunnel testing conditions are generally characterized by the flight regime they capture, pressure and temperature capabilities, and its overall simulation type. Regular wind tunnels are capable of simulating regular atmospheric conditions, but more specialized conditions can be simulated through the use of pressurized or cryogenic tunnels. For example, the use of cryogenic tunnels enables engineers to match both Re and Mach numbers.

For the test article and testing conditions, engineers must first determine what type of system they wish to represent (wing, fuselage, etc.), and then an appropriate size and scale can be determined. The scale is dependent on several things, including the wind tunnel conditions, test section size, wall effects, and other factors. Furthermore, the test section size and desired testing conditions may require engineers to utilize a half model instead of a full model. For instance, if one is trying to collect higher RE data, a half model may be more advantageous in achieving those conditions.

There are advantages and disadvantages to using a half model. The use of a half model allows for a larger test article to be utilized, which means more instrumentation could be placed on the test article and engineers are less likely to deal with thin trailing edge issues. However, more corrections may have be introduced to the resulting data during post-processing due to the absence of the entire system.

The requirements of the experiment also determine what components should be represented on the test article, such as the horizontal and vertical tails and high lift devices. The test article can also have a variety of different powered capabilities. It can be powered or unpowered, with a variety of options for both. For powered test articles, it could include ejectors, electric fans, blown nozzles, etc. For unpowered test articles, flow through nacelles could be present with or without mass flow plugs.

Once the details of the test article have been more defined, other similitudes should be investigated. Geometrically scaling is only one aspect that must be considered when designing the test article and conditions. As previously mentioned, some similarity parameters are more important than others depending on the phenomena under investigation. Aeroelastic tests can be either static or dynamic, and the selection of static or dynamic impacts how the test article must be scaled (and manufactured) with respect to the full scale system. For static tests, a model must be properly scaled for mass, mass distribution, and elasticity. Furthermore, the load factor, dynamic pressure, and Mach number should be taken into consideration. For dynamic tests, it is important that the mass distribution is scaled for inertial effects in addition to the static testing requirements. For rigid models under incompressible flow conditions, the model should be geometrically scaled appropriately, with consistent angles of attack, sideslip angles, control surface positions, and Re number should be matched. When the flow conditions are in the compressible range, Mach number should also be matched in addition to the other conditions.

As stated previously, Re number is important and matching Re number can be difficult because most tunnels cannot come close to flight Re except for small vehicles – so scaling is almost always necessary; furthermore, when Mach number must also be matched, such as in a compressible flow test, it becomes more difficult. There are two main ways to accomplish the matching of both Re number and Mach. First, Re number can be approximated by fixing the model's lifting surface s (I don't know that this means? Making a large/full size model?). If this is not sufficient, the second method is to vary the wind tunnel pressure and temperature, potentially through the use of a cryogenic tunnel. If the phenomena under investigation is believed to not be sensitive to RE, a conventional, non-cryogenic tunnel can be utilized.

Upon selection of the test specimen, how it will be mounted must also be determined. Free flying is less common and is usually done to conduct a qualitative evaluation of the dynamic stability and control of the model. For mounting, a test article can be floor mounted, sidewall mounted, or sting mounted. There are several options for sting mounting, such as straight, upper swept blades, and lower swept blades.

As characteristics of the test specimen are being defined, the type of sensing and its placement must also be finalized. The type of data the experiment must result in defines the type of sensing that must be included in the experimental setup. As shown in Table 1, there are several different types of sensing that can be included during a wind tunnel testing campaign, such as flow visualization, pressure measurements, and flow speed. Taking a closer look into the pressure measurements, there are several different techniques that can be utilized such as pressure taps and pressure sensitive paint (PSP). Pressure taps can provide a discretized pressure distribution across the surface, such as the chord of the airfoil. Depending on the level of fidelity required from the data, pressure taps may provide a sufficient source of information. However, pressure taps do interfere with the flow and can cause impacts downstream.

PSPs, in contrast, do not interrupt the flow field and can be potentially utilized in both steady and unsteady flows. However, PSPs require calibration so other pressure measurement sources (i.e. pressure taps) must be minimally present to provide the appropriate calibration data. Therefore, PSPs can provide the ability to collect continuous pressure measurements across the test article which can be very valuable when trying to comprise a solid aerodynamic database.

Placement of sensors is also important to ensure the quality of the data collected. Sensors can be concentrated in a specific part of the test article or spread throughout the test article, such as along the span or the chord. For some sensing capabilities, such as PSP, they could be considered as more of a continuous placement throughout the test article.

With all of these attributes in mind, the first two experimental campaigns for the CRM configuration were dissected. These two sets of tests, both performed in 2010, were conducted in the NASA Langley Transonic Facility (NTF) and the NASA Ames 11ft Transonic Wind Tunnel (TWT). The details of both experiments are summarized through the text color in Table 1. The differing text color of the cells in Table 1 demonstrate how the morphological analysis is intended to be used for detailed experimental planning. The blue text indicates a setting for the NTF tests, red text indicates a setting for the TWT tests, and purple indicates a setting utilized for both sets of tests.

The NTF facility is a conventional closed circuit design that is capable of both standard operating conditions and fully cryogenic conditions. It can simulate subsonic to low supersonic flight regimes. The test section for the NTF is 8.2ft by 8.2 ft and the CRM experiments utilized a slotted wall boundary. The TWT is also a closed-circuit design capable of variable pressure operations. The test section size for the TWT is 11ft by 11ft and a porous boundary was utilized. Further details of the NTF and NASA Ames facilities are publicly available.[23]

For both sets of tests five different configurations were tested. The configurations were a wing/body configuration, a wing/body/nacelle/pylon configuration, and three wing/body/tail configurations. While the CRM is not an actual airplane, it is considered by some a 2.7% scale of a twin aisle class vehicle. The models were considered unpowered and included flow through nacelles. No control surfaces or high lift surfaces were included. For mounting, both sets of test were sting mounted, specifically upper swept strut sting in position of the vertical tail.

Both the NTF and TWT tests provided force and moment information, utilized pressure taps for steady pressure measurements and Kulites for unsteady pressure measurements. The TWT tests also utilized PSP for additional steady pressure measurements. Flow speed measurements and visualization was taken with Particle Image Velocimetry (PIV) for the TWT tests and model deformation data was gathered through videogrammetry for the NTF tests.

4.4 Test Case Design of Experiment

After the details of the experiment are defined in terms of the wind tunnel, test article, and instrumentation, the actual test matrix for the experimental runs must be set. The points in the

Table 1: Notional Wind Tunnel Testing Morphological Analysis
(Blue=NTF, Red=TWT, Purple=Both)

	Class of Experiment	Aerodynamic	Acoustic	Icing	Other	
Wind Tunnel	**WT Type**	Regular-Atmospheric	Cryogenic	Pressurized	Pressurized + Cryogenic	
Wind Tunnel	**Layout**	Open return	Closed return	Double return	Annular return	
Wind Tunnel	**Max Speed Regime**	Subsonic	Transonic	Supersonic	Hypersonic	
Wind Tunnel	**Stagnation Pressure**	Atmospheric	Variable Pressure	Variable Temperature		
Wind Tunnel	**Maximum Temperature**	Ambient	550°R	580°R	600°R	other
Wind Tunnel	**Test Gas**	Air	Nitrogen	R134	Other	
Wind Tunnel	**Test Section Design**	Closed	Open	Reconfigurable	Slotted wall	Solid Wall
Wind Tunnel		Porous				
Wind Tunnel	**Test section size**	7x9ft	11x11ft	40x40ft	80x80ft	Other
Sensing	**Steady pressure**	Pressure taps	Pressure sensitive paint (PSP)			
Sensing	**Unsteady pressure**	Kulites	Microphones	PSP	Pressure taps	
Sensing	**Off surface measurement**	Hot Wire Anemometry	Laser Doppler Velocimetry (LDV)	Doppler Global Velocimetry (DGV)	Particle Image Velocimetry (PIV)	
Sensing	**Control Surface Deflections**	Stereo Pattern Tracking (SPT)	Other			
Sensing	**Model Deformation**	Videogrammetry	SPT	Fiber Optics		
Sensing	**Transition**	Sublimation	Evaporation	Other		
Sensing	**Visualization**	Smoke	DGV	LDV	Tufts	Surface oil
Sensing		Sublimation	Schlieren photography	PIV	PSP	other
Test Article and Conditions	**Model Scale**	100%	50%	1/32	1/64	other
Test Article and Conditions	**Model Size**	Full	Half	Other		
Test Article and Conditions	**Model Power Capability**	Powered	Unpowered			
Test Article and Conditions	**High Lift System**	Conventional	Active Flow Control	Circulation Control	other	
Test Article and Conditions	**Model control surfaces/ high lift**	Fixed	Moveable	Ailerons	Flaps	Flaperons
Test Article and Conditions		Spoilers	Horizontal tail	Vertical tail	None	Other
Test Article and Conditions	**Model mounting**	Sting	Sidewall mounted	Floor mounted	Other	
Test Article and Conditions	**Force + Moment**	Force + Moment Balance				
Test Article and Conditions	**Sensor Placement**	Concentrated	Span-wise	Chord-wise	Continuous	other
Test Article and Conditions	**Similarity**	Re	M	ST	Re+M	Re+M+ ST

test matrix can be enumerated in terms of Mach number, angle of attack, Re, etc. Furthermore, if high lift and/or control devices are being tested, the angles of deflection will also have to be factored into the DOE settings.

If the objective of the wind tunnel test is to create data for an aerodynamic database, engineers must first determine what data points are missing from their existing set, if one exists. Often engineers need to prioritize the data points they capture due to time and resource constraints. Therefore, the use of DOE techniques is very important to ensure the maximum amount of value can be gained from the runs that are performed.

For the NTF tests conducted in 2010, three different Re numbers were examined: 5 million, 19.8 million, and 30 million. Angle of attack sweeps were also performed. For the Re number of 5 million the angle of attack was varied from -3 degrees to 12 degrees. For the other two Re numbers the angle of attack was varied from -3 degrees to 6 degrees. The temperatures of the runs varied from -250F to 120F. Also, for the Re number of 19.8 million two different dynamic pressures were examined. The testing at NTF took approximately 6 weeks. There were 259 runs with over 3,000 data points collected.

For the TWT tests one Re number was examined, which was a Re number of 5 million. An angle of attack sweep was performed that went from -3 degrees to 12 degrees. Overall, the tests conducted in the TWT took 5 weeks. There were 273 runs with over 3,000 data points collected.

4.5 Test Case Conclusions

As stated, the objectives for the first two sets of CRM experiments in the NTF and TWT facilities twofold. First, they aimed to capture general, non-existent performance data of the geometry. Second, the tests aimed to capture advanced measurements through the use of new measurement capabilities. Furthermore, data captured from both of these tests were to be used for validation purposes of calculations performed at the DPW-IV.

As summarized in the previous section, multiple model configurations were tested in both facilities. The introduction of a nacelle/pylon and different horizontal tail configurations provided a comprehensive assessment of the CRM geometry beyond a basic wing/fuselage configuration. Also, capturing deformations of the model, as was done in the NTF experiments, helps collect information on the model geometry definition when subject to aerodynamic loads.

In both sets of experiments angle of attack and Mach number sweeps were performed. This helps ensure that data from throughout the flight envelope, beyond cruise conditions, would be captured. The NTF tests captured both low and high Re number data, while the TWT tests only captured a single low Re number. However, more sensing capabilities were utilized in the TWT tests so more data was acquired for the 5 million Re number, especially when combined with the 5 million Re data from the NTF tests.

Recalling the objectives of DPW-IV, data for a 5 million Re number at M=0.85 was required at different angles of attack; data for a 5 million Re number at a sweep of Mach numbers; and data at both low and high Re numbers at Mach=0.85 was needed for validation purposes. As described in the previous sections, the test matrices gathered data at or near the settings established in the three DPW-IV cases.

In summary, the first two CRM tests captured the experimental data they aimed to acquire. The objectives set by the DPW-IV, gathering validation data, was met. Furthermore, general data to adequately capture the new geometric configuration was gathered for a variety of different Re numbers and testing conditions. Two different facilities and a total of 11 weeks were required to capture all of this data.

5 Conclusions

Newly developing technologies will be key for next generation aircraft systems to meet their performance goals. As previously stated, determining which technologies to pursue is difficult under the large amount of uncertainty that exists. Engineers need sound processes driven by systems engineering approaches to adequately design experiments with the purpose of increasing technology readiness and decreasing uncertainty. The research presented herein presents one approach that aims to contribute to this ultimate objective.

The three-phased approach outlined focuses on setting clear experiment requirements, designing experiments that will meet those requirements, and generating key data points that will provide the information required. The detailed discussion provided surrounding the NASA Common Research Model (CRM) demonstrated how the immense amount of detail and planning that goes into wind tunnel experimentation can be formalized through this three-phase approach. It was also demonstrated how the morphological analysis technique can be leveraged to help with mapping experimental requirements to the testing attributes.

Going forward, synthesizing information from quantitative, probabilistic system performance assessments with qualitative readiness assessments for the purpose of technology development experimentation planning will be key to ensuring technologies are developed in a streamlined, efficient manner. Combining all of this information has the potential to provide the clearest picture of the development status of a single technology, group of technologies, or system, as well as characterization of its predicted performance attributes. This synthesis of information will aid risk-informed technology experiment planning decisions throughout technology and system development.

The next steps in this research process should focus on validating the approach on a real-world technology development program. Validating the approach will involve identifying an appropriate technology program to utilize and identifying the following key information: vehicle configurations and classes for consideration, technology portfolio, technology impact information, identification of key uncertainty sources and data required to quantify them, system level goals and metrics of interest. This information will be utilized, along with the approach outlined herein, to demonstrate how experiments could be planned to achieve key readiness milestones and reduce the performance uncertainty.

References

[1] K. N. Gatian, “A Quantitative, Model-Driven Approach to Technology Selection and Development through Epistemic Uncertainty Reduction,” Georgia Institute of Technology, 2015.

[2] K. N. Gatian and D. N. Mavris, “Enabling Technology Portfolio Selection through Quantitative Uncertainty Analysis,” in *AIAA AVIATION 2015*, 2015, no. June, pp. 1–28.

[3] K. N. Gatian and D. N. Mavris, “Facilitating Technology Development Progression through Quantitative Uncertainty Assessments,” in *AIAA AVIATION*, 2014, pp. 1–16.

[4] J. C. Mankins, “Technology Readiness Levels,” 1995.

[5] K. N. Gatian and D. N. Mavris, “Planning Technology Development Experimentation through Quantitative Uncertainty Analysis,” in *54th AIAA Aerospace Sciences Meeting*, 2016.

[6] W. Oberkampf and C. Roy, *Verification and Validation in Scientific Computing*. New York, NY: Campridge University Press, 2010.

[7] B. E. Robertson, “A Hybrid Probabilistic Method to Estimate Design Margin,” Georgia Institute of Technology, 2013.

[8] W. Yao, X. Chen, W. Luo, M. van Tooren, and J. Guo, “Review of uncertainty-based multidisciplinary design optimization methods for aerospace vehicles,” *Prog. Aerosp. Sci.*, vol. 47, no. 6, pp. 450–479, Aug. 2011.

[9] H. N. Najm, “Uncertainty Quantification and Polynomial Chaos Techniques in Computational Fluid Dynamics,” *Annu. Rev. Fluid Mech.*, vol. 41, no. 1, pp. 35–52, Jan. 2009.

[10] M. E. Pate-Cornell, “Uncertainties in risk analysis : Six levels of treatment,” *Reliab. Eng. Syst. Saf.*, vol. 54, pp. 95–111, 1996.

[11] M. Stamatelatos and H. Dezfuli, “Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners,” Washington, DC, 2011.

[12] B. Peherstorfer, K. Willcox, and M. Gunzburger, “Survey of multifidelity methods in uncertainty propagation , inference , and optimization,” *Preprint*, pp. 1–57, 2016.

[13] A. Saltelli, “Sensitivity analysis for importance assessment.,” *Risk Anal.*, vol. 22, no. 3, pp. 579–

90, Jun. 2002.

[14] E. A. Bjorkman, “Test and Evaluation Resource Allocation Using Uncertainty Reduction as a Measure of Test Value,” George Washington University, 2012.

[15] S. Sankararaman, K. McLemore, S. Mahadevan, S. C. Bradford, and L. D. Peterson, “Test Resource Allocation in Hierarchical Systems Using Bayesian Networks,” *AIAA J.*, vol. 51, no. 3, pp. 537–550, Mar. 2013.

[16] M. C. Largent, “A Probablistic Risk Management Based Process for Planning and Management of Technology Development,” Georgia Institute of Technology, 2003.

[17] G. Wissema, “Morphological Analysis: Its application to a company TF investigation,” *Futures*, no. April, pp. 146–153, 1976.

[18] J. Utterback, “New Approaches to Technological Forecasting,” *Bus. Horiz.*, no. December, 1970.

[19] B. Yoon, R. Phaal, and D. Probert, “Morphology analysis for technology roadmapping : application of text mining,” *Res. Dev. Manag.*, vol. 38, no. 1, pp. 51–68, 2008.

[20] M. R. Kirby, “A Methodology for Technology Identification, Evaluation, and Selection in Conceptual and Preliminary Aircraft Design,” Georgia Institute of Technology, 2001.

[21] C. H. Wolowicz and J. S. Bowman, “Similitude Requirements and Scaling Relationships as Applied to Model Testing,” 1979.

[22] A. N. Watkins, B. D. Leighty, W. E. Lipford, O. D. Wong, D. M. Oglesby, and J. L. Ingram, “Development of a pressure sensitive paint system for measuring global surface pressures on rotorcraft blades,” in *ICIASF Record, International Congress on Instrumentation in Aerospace Simulation Facilities*, 2007.

[23] M. B. Rivers and A. Dittberner, “Experimental Investigations of the NASA Common Research Model in the NASA Langley National Transonic Facility and NASA Ames 11-Ft Transonic Wind Tunnel (Invited),” *AIAA Pap.*, 2011.

[24] M. Rivers and S. Balakrishna, “NASA Common Research Model Test Envelope Extension with Active Sting Damping at NTF,” in *32nd AIAA Applied Aerodynamics Conference*, 2014.

[25] S. Koga, M. Kohzai, M. Ueno, K. Nakakita, and N. Sudani, “Analysis of NASA Common Research Model Dynamic Data in JAXA Wind Tunnel Tests,” in *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2013.

[26] C. A. Broughton, A. Benmeddour, Y. Mebarki, and M. B. Rivers, “Experimental Investigations of the NASA Common Research Semi-Span Model in the NRC 5-ft Trisonic Wind Tunnel,” in *2018 Aerodynamic Measurement Technology and Ground Testing Conference*, 2018.

[27] A. Cartieri, D. Hue, Q. Chanzy, and O. Atinault, “Experimental Investigations on the Common Research Model at ONERA-S1MA - Comparison with DPW Numerical Results,” in *55th AIAA Aerospace Sciences Meeting*, 2017.

[28] J. C. Vassberg and Et.al, “Summary of the Fourth AIAA CFD Drag Prediction Workshop,” *AIAA Pap.*, 2010.

[29] D. W. Levy *et al.*, “Summary of Data from the Fifth Computational Fluid Dynamics Drag Prediction Workshop,” *J. Aircr.*, 2014.

[30] J. Vassberg, M. Dehaan, M. Rivers, and R. Wahls, “Development of a Common Research Model for Applied CFD Validation Studies,” in *26th AIAA Applied Aerodynamics Conference*, 2008.

Copyright Statement