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NLR-TP-2016-449 | May 2017

Integrated energy and power management: validation testing for aerospace vehicles

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EXECUTIVE SUMMARY

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Integrated energy and power management: validation testing for aerospace vehicles

Problem area

With legacy aircraft, operations as well as system upgrades are limited by the available energy and power management capabilities. Subsequently, the power, electrical distribution, and thermal management backbone capacity limits the ability to achieve maximum performance over the extended life-time. To improve this situation, there is an urgent need for a high-level integrated analysis approach coupled with growth management to assess the feasibility of potential upgrades and subsequent capability margins for future operations.

Description of work

The objective of the current work is to develop and demonstrate a robust validation testing approach that transcends beyond the component-only focus to one that addresses the vehicle in its entirety and throughout the vehicle life-cycle. A structured technical and organizational approach to integrated dynamic energy and power management research is outlined from an integrated vehicle and dynamic subsystem/component perspective. Rational approaches to energy,

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power, and thermal management model-based engineering coupled with growth management are developed. These approaches combine physics-based and statistical modeling, and component and system validation testing on baseline airframe(s) in a flight simulated environment. The newly developed techniques are also expected to define life-cycle operational support requirements for future high power aircraft architectures. An integrated energy and power management (IEPM) laboratory has been set up hosting two airframes (USAF airframe and RNLAF airframe), a data acquisition system, and a simulation cockpit. The IEPM-laboratory is intended for validation testing of components and of interacting systems.

Results and conclusions

From the results obtained within the sketched scope of work, it is concluded that experimental data of individual system component tests are not alone sufficient. Laboratory tests on an integrated airframe with interacting subsystems are needed to properly define requirements for effective validation testing and to support a well-posed validation testing approach. These approaches are also expected to offer insight in the definition of life-cycle operational support requirements for future high power aircraft architectures. The current scope of testing for components as well as interacting systems (hardware-in-the-loop) is necessary to define the ultimate flight test system such that appropriate validation data will be registered in flight. The carefully designed flight test metrics will provide insight into the deviation mechanisms and the required corrections on the laboratory tests to map laboratory test results onto the real flight test data.

Applicability

The IEPM laboratory assets will be utilized to conduct research in defining model-based engineering concepts coupled with growth management to effectively assess the feasibility of potential upgrades and subsequent capability margins for current as well as future operations and platforms. These approaches are also expected to asses and define life-cycle operational support requirements for future high power aircraft architectures. Component testing combined with both airframes provide a component to subsystem to vehicle path to define approaches to formulating and evaluating validation testing concepts.

GENERAL NOTE
This report is based on a presentation held at the AIAA Science and Technology Conference, San Diego, January 4-8, 2016.

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Abbreviations

ACRONYM	DESCRIPTION
ANOVA	Analysis of variance
AVS	Air vehicle system
BPPoC	Bleed power proof of concept
CSD	Constant speed drive
DoX	Design of experiments
FOHXPoC	Fuel oil heat exchanger proof of concept
HIL	Hardware in the loop
HPMS	Heat and power management simulator
IEPM	Integrated energy and power management
LDS	Low discrepancy sequence
M&S	Modeling and simulation
NLR	Netherlands Aerospace Centre
PI	Proportional integral
PTO	Power take off
rms	Root mean square
RNLAF	Royal Netherlands Air Force
rpm	Rotations per minute
RTM	Reduced thermal model
SPPoC	Shaft power proof of concept
UP	Uncertainty propagation
UQ	Uncertainty quantification
USAF	United States Air Force

Integrated Energy and Power Management: Validation Testing for Aerospace Vehicles

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The structured technical and organizational approach to integrated dynamic energy and power management research is outlined from an integrated vehicle and dynamic subsystem/component perspective. This approach combines physics-based and statistical modeling and component and system validation testing on baseline airframe(s) in a flight simulated environment. It is concluded that experimental data of individual system component tests are not alone sufficient. Laboratory tests on an integrated airframe with interacting subsystems are needed to properly define requirements for effective validation testing needed to support robust model-based engineering and life-cycle growth management. The objective is to develop and demonstrate a robust validation testing approach that transcends beyond the component-only focus to one that addresses the vehicle in its entirety and throughout the vehicle life-cycle.

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I. Introduction

With legacy aircraft, operations as well as system upgrades are limited with respect to an available energy and power management capability. Subsequently, the power, electrical distribution, and thermal management backbone capacity limits the extensity to achieve maximum performance over the extended life-time. Rational approaches to energy, power, and thermal management model-based engineering coupled with growth management are needed to effectively assess the feasibility of potential upgrades and subsequent capability margins for future operations. These approaches are also expected to define life-cycle operational support requirements for future high power aircraft architectures. As a demonstration of coupled model-based engineering and growth management, well posed modeling and simulation (M&S) and validation testing can be exploited with a view toward evaluation of the growth potential of the electrical system loads. The subsequent impact on the power, electrical distribution, and thermal management backbone coupled to the air vehicle structure and engine can then be assessed. Furthermore, since these backbone components are integrated with electrical system loads and aircraft subsystems, their integration often results a complex interaction of dynamic loads due to pilot action. As a result, system multidisciplinary complexity must be taken into account to properly define and assess energy and power management capability. It is concluded that experimental data of individual system component tests are not alone sufficient. Laboratory tests on an integrated airframe with interacting subsystems are needed to properly define requirements for effective validation testing and to support a well-posed validation testing approach.

II. General Concepts

A. Role of Modeling and Simulation (M&S)

In general, a robust M&S framework requires an expanded all-inclusive vision with a clear definition for validation testing at model inception, Figure 1. As such, the development of physics-based models is first approached by defining the physical and statistical relevance for experimental validation. This must be taken into account at the inception and development of the physics-based models. The role then of M&S is expanded to focus on the design space residual mapping, input-to-output variance propagation as well as defining the optimal validation testing that minimizes experimental activities. Shown in Figure 1 is an example of design space residual mapping for a generator using a generic physical model coupled to a well-defined approach to validation testing.

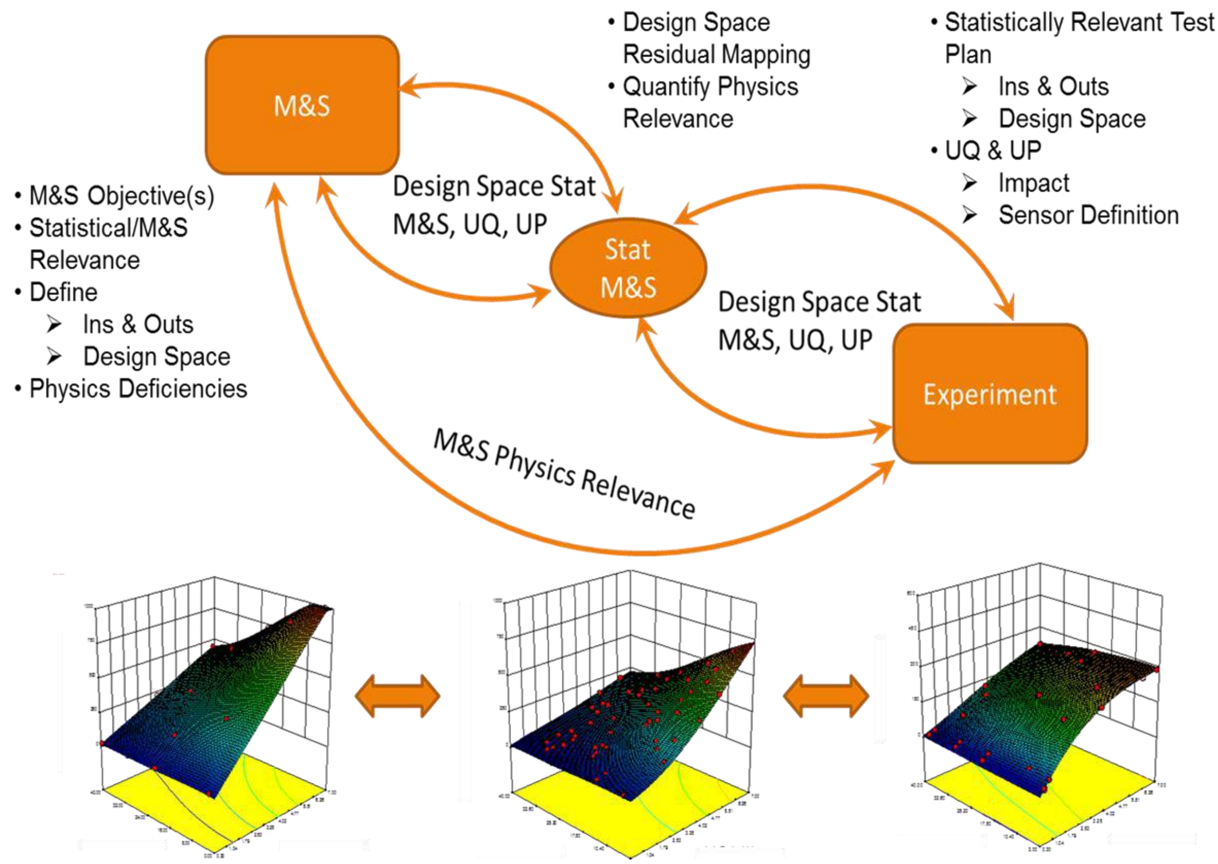


Figure 1. Role of M&S expanded.

B. Design of Experiments

Design of Experiments (DoX) is the development of a statistically based information-gathering exercise where variability is present, and may be able to be influenced by the experimenter (a controlled experiment), partially controlled (pseudo-controlled experiment) or not controlled (a random experiment)[1]. In any case, there is some knowledge of the system response quantity of interest, the controllable inputs or factors, the ranges over which the inputs may be varied, and an expectation of a response relative to the reference no-response or null condition.

Surrogate models are often the product of the DoX process and can be very useful tools for the researcher. Development of a surrogate model is generally accomplished in many steps. First, prototypes are performed in order to better understand the physical relationships of the process(es). The results of these initial queries are used to better understand the responses and ranges of input variables of interest. Next, a set of screening runs are performed in order to determine if a relationship exists between any of the input variables upon the response of interest. If a relationship is likely to exist, that input variable is retained for further study. Conversely, if a relationship between input variable and responses is *not* likely to exist, then that input variable is removed from consideration in the surrogate model. This is not to say that the variable is not required for the model, it is only to be interpreted that the screened out variable is not a design "driver" and its value may be set to some nominal operating point. After the screening and prototypes are performed, the surrogate model may be developed.

A workflow representation of the surrogate model development (system identification) process is illustrated in Figure 2. The process follows a sequentially ordered methodology as follows:

1) Development of the framework for determination of the surrogate model
    a. Calibration data is developed using DoX[1] that supports uncertainty quantification (UQ) via truncation error specification and variance identification in the surrogate model,
    b. A class of surrogate models is proposed along with a set of unknown parameters for those models.
2) The calibration process produces results for the class of proposed models along with statistical quality metrics for how well each model fits the calibration data as well as how well the model is likely to properly predict future data.
3) Use statistical processes (e.g. ANalysis Of Variance or ANOVA, Deep[2], statistical significance along with hypothesis testing[3], *a posteriori* transformation, etc.) to select the most parsimonious model and parameter set that best minimizes the variance of the models as well as best estimates the current and future data.
4) Develop a set of pseudo-random input data for corroboration of the parsimonious surrogate model.
5) Perform predictions of the surrogate model using the corroboration data and compare the results to those of the original model using the same corroboration data.

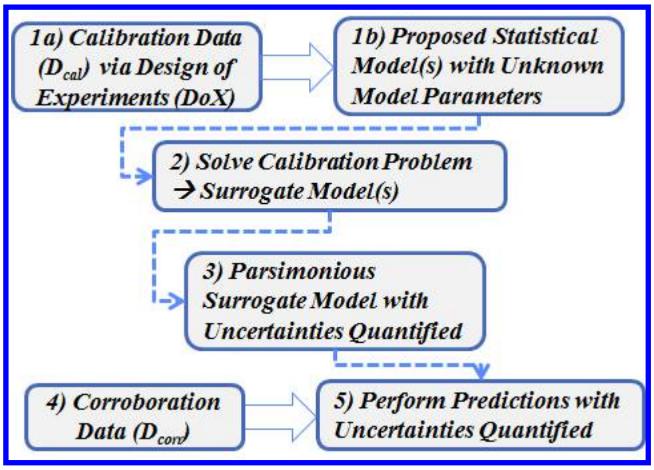


Figure 2. Work flow representation of the surrogate model development (system identification).

III. Generator Validation Testing

A. Generic Generator Model

An electrical model of a generic synchronous generator system was developed to provide the estimation of machine behavior[4]. This model was used to develop statistical models which encompass the physics-behavior and provide guidance for experimental validation using a representative generator for testing.

The generator model assumed a permanent magnet generator design specific to a 40 kVA, 12 krpm, 115 Vrms 3-phase, 400 Hz electrical machine. The model design is based off a 3-stack generator concept which includes a permanent magnet generator, synchronous exciter, and synchronous generator, is used to develop a linear, electrical model of the generator system. However, for implementation, a 2-stack linear model for which the exciter field voltage was assumed to be controllable to the desired level in order to regulate the 3-phase voltage bus to approximately 115 Vrms. Therefore, only the synchronous generator and exciter were designed. Machine parameters were inserted into a Simulink 2-stack linear generator model. The 2-stack model includes a synchronous generator and exciter block, basic proportional, integral (PI) control of the exciter field voltage and a resistive 3-phase load. Figure 3, Figure 4, and Figure 5 show the various stages of the 2-stack model developed. In the real system, the source for the exciter field voltage is from the power generated by the permanent magnet generator. Some voltage regulation and basic switching control of the permanent magnet generator's output can tune the exciter voltage to the appropriate level for proper voltage bus control on the output. For the validation testing discussed, the generator controller was bypassed resulting in only the exciter voltage and generator load as the two primary model inputs of interest.

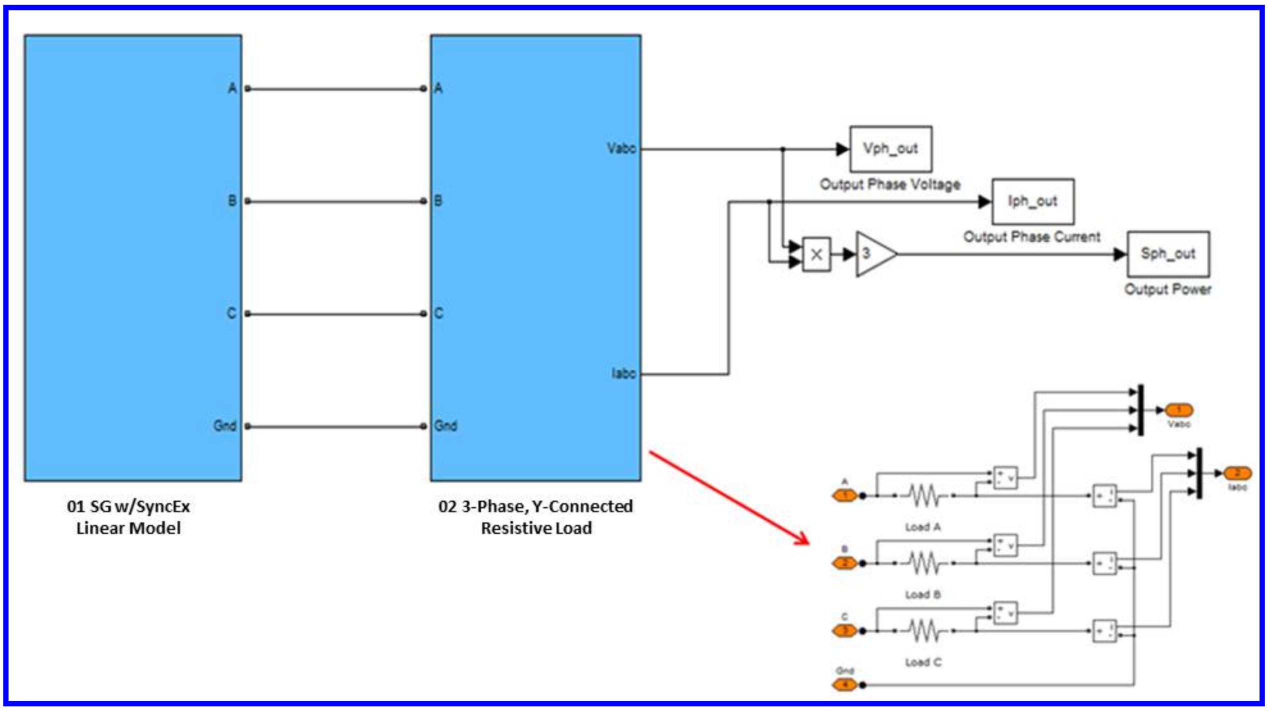


Figure 3. 2-Stack synchronous generator model (top level).

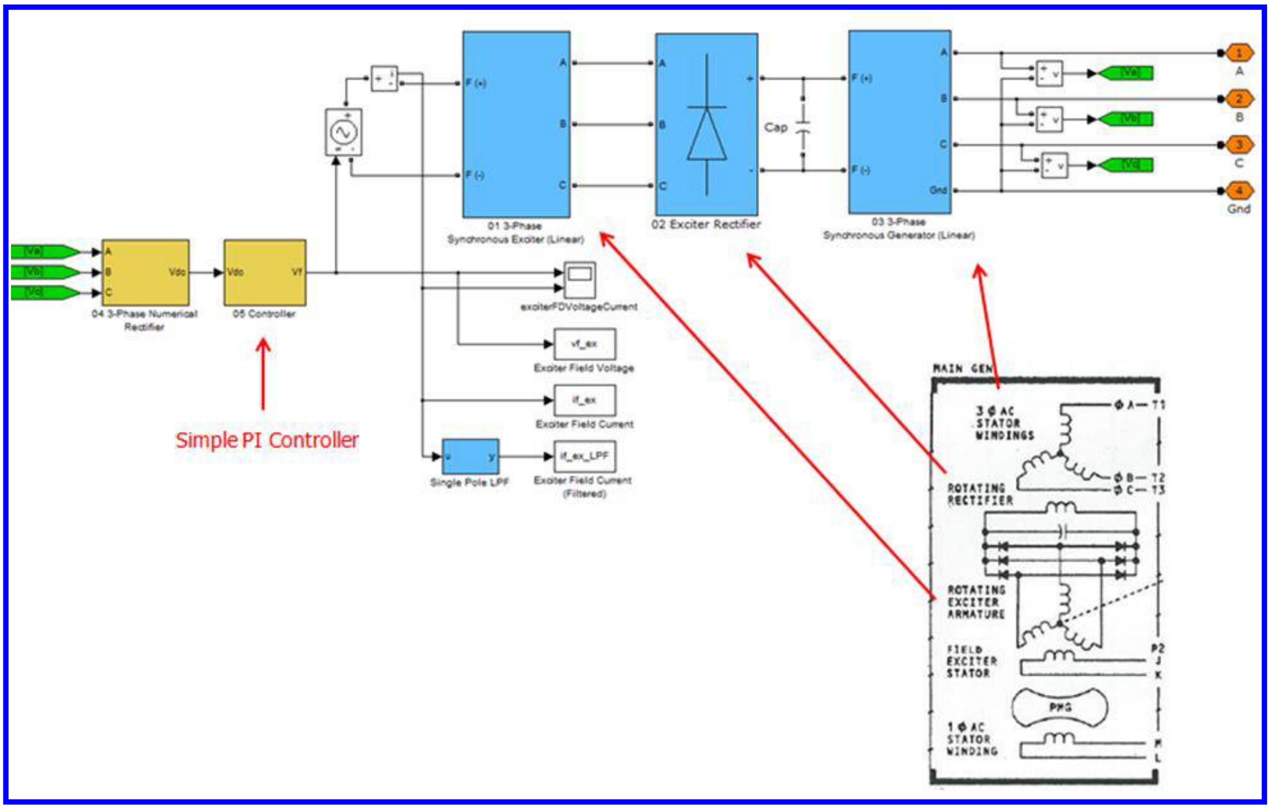


Figure 4. 2-stack synchronous generator model (subsystem level).

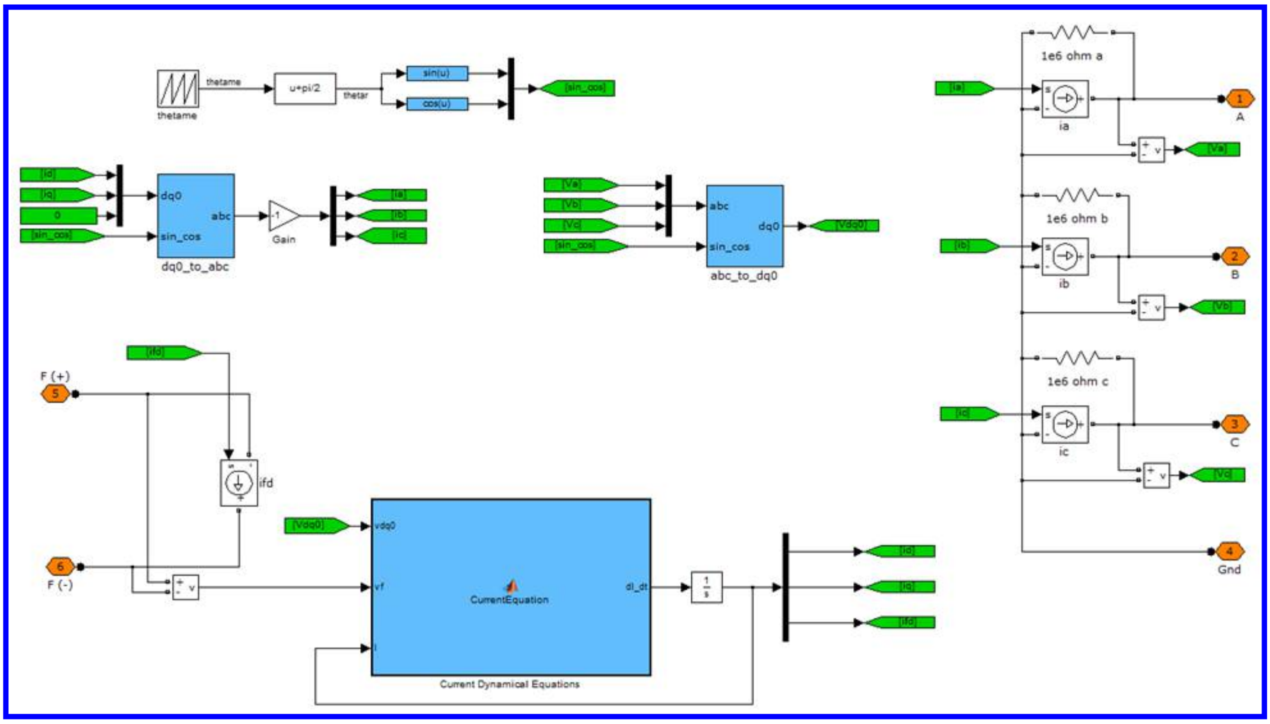
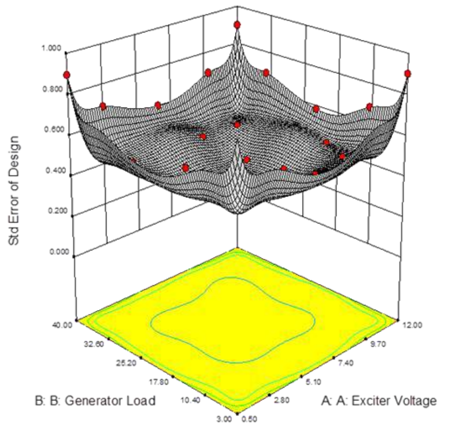


Figure 5. 2-stack synchronous generator model (synchronous generator and exciter blocks).

B. Generator Validation Testing

To initiate the validation testing process, the generic generator physics-based model, as discussed, was run throughout the design space. A test plan was developed considering the two primary model inputs of interest, exciter voltage and generator resistance load, and outputs, line-to-line peak phase voltage and peak phase current. An optimal quartic statistical model was chosen to define a 45-point test plan taking into account the two primary model inputs ranges; exciter voltage, 0.50-12V, and generator resistance load, 3-40kW. The resultant statistical standard model error is shown in Figure 6. Also shown in Figure 6 are the output R-squared values and resulting surrogate polynomial output response surfaces from the results of the 45-point test plan.



	R-Squared	Adj R-Squared	Pred R-Squared
Voltage & Current	1.0	1.0	1.0

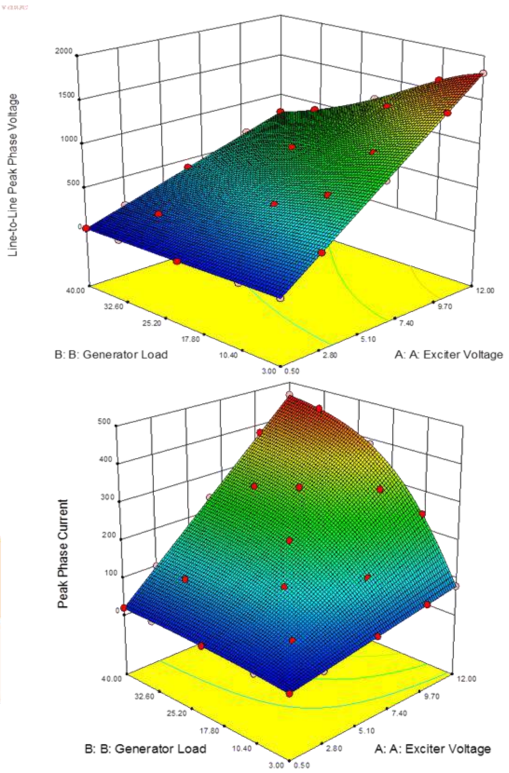


Figure 6. Quartic statistical model standard error and resulting voltage and current response surfaces derived from generic generator model.

The resulting surrogate polynomials were then corroborated to the generic generator physics-based model by defining a new random set of inputs using a 100-point low discrepancy sequence (LDS). Figure 7 shows the random LDS inputs and resulting output fractional error, peak phase voltage and peak phase. Now from the surrogate polynomials one can define the measurement uncertainties needed for the experimental testing. It also follows that one can prescribe and implement the same test plan that was used to run the generic generator physics-based model to be experimental test plan.

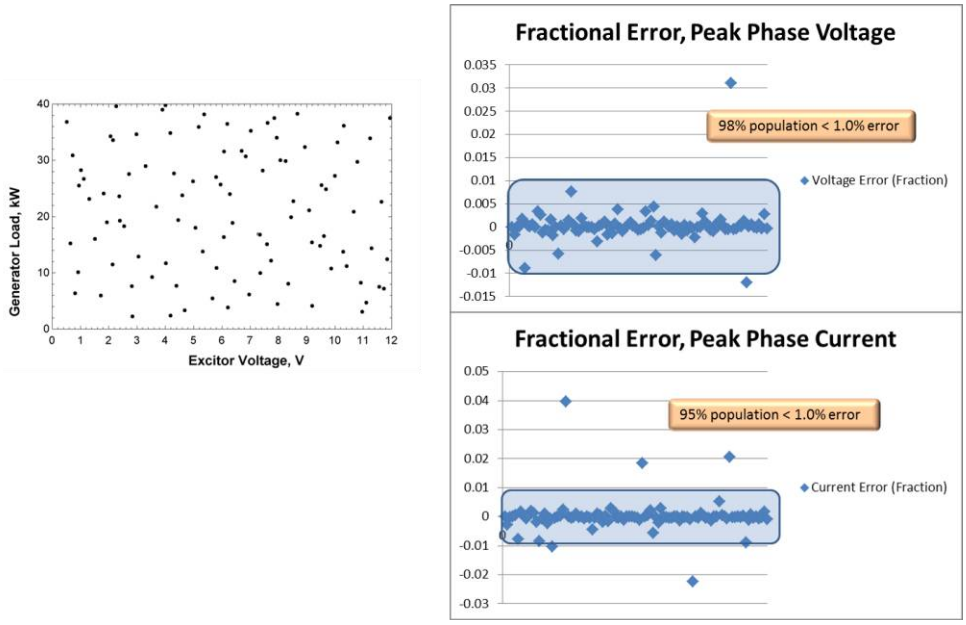


Figure 7. Corroboration of surrogate polynomial model to the generic generator physics-based model showing the random inputs and fractional error for outputs, peak phase voltage and current.

Figure 8 shows the experimental testing configuration. The physical generator, which includes the electrical machine, constant speed drive (CSD), and integrated oil pump, was mounted on a drive stand. The drive stand was operated at ~5,000rpm and within the CSD input range of 4500-9000rpm. For initial experimental testing the CSD oil cooling loop was pumped through a process water heat exchanger. A resistance electrical load was applied to the generator using 3-phase resistance load bank as also noted in Figure 8. The load bank is also capable of applying an inductance electrical load to the generator for later experimental testing. For initial experimental testing, the generator was operated with short load durations to electrically steady-state conditions. No calorimetric measurements were taken and oil temperatures did not exceed 115ºF. The resultant experimental statistical standard model error is shown in Figure 9. Also shown in Figure 9 are the output R-squared values and resulting surrogate polynomial output response surfaces from the results of the 45-point test plan for the experimental testing.

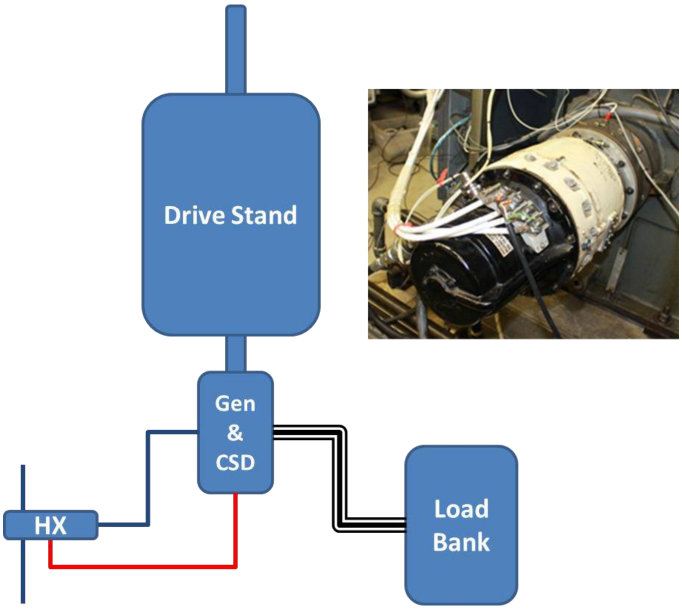
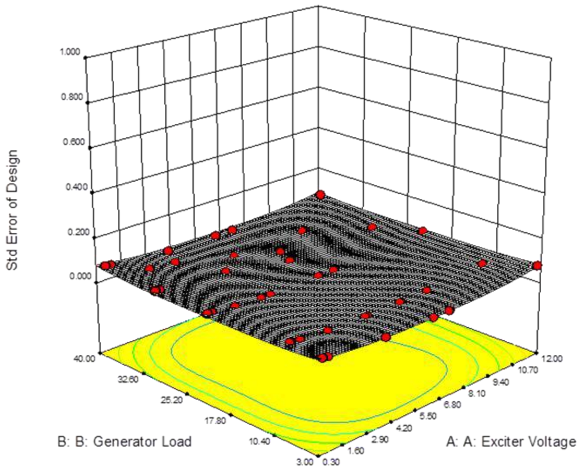
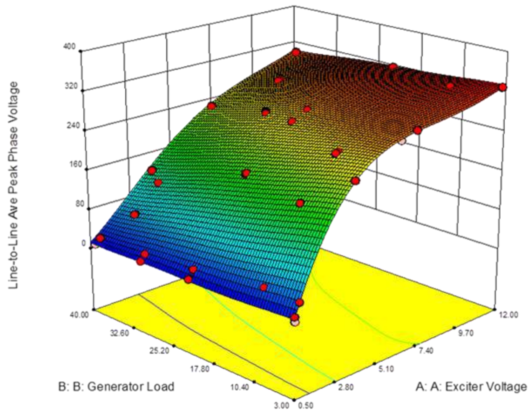


Figure 8. Experimental testing configuration showing installed generator and constant speed drive (CSD).





	R-Squared	Adj R-Squared	Pred R-Squared
Ave Peak Voltage	0.9997	0.9997	0.9997
Ave Phase Current	0.9999	0.9999	0.9999

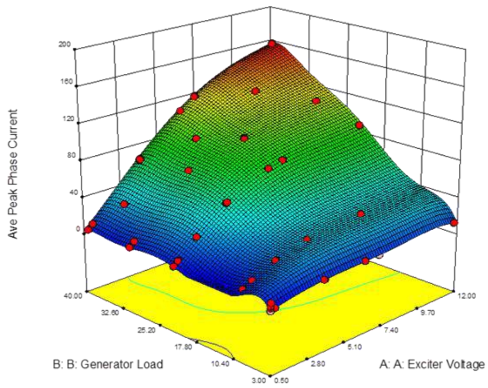


Figure 9. Experimental statistical model standard error and resulting voltage and current response surfaces derived from experimental test plan.

The resulting surrogate polynomials shown in Figure 6 and Figure 9 can be used to determine the design space residuals for both the line-to-line peak phase voltage and peak phase current. Again, a random set on input values for the exciter voltage and generator resistance load, similar to that shown in Figure 7, were inputted for each output set of generator model and experimental surrogate polynomials. The design space residual maps were then defined as a surrogate polynomial function. The resulting residual maps across the design space are shown in Figure 10.

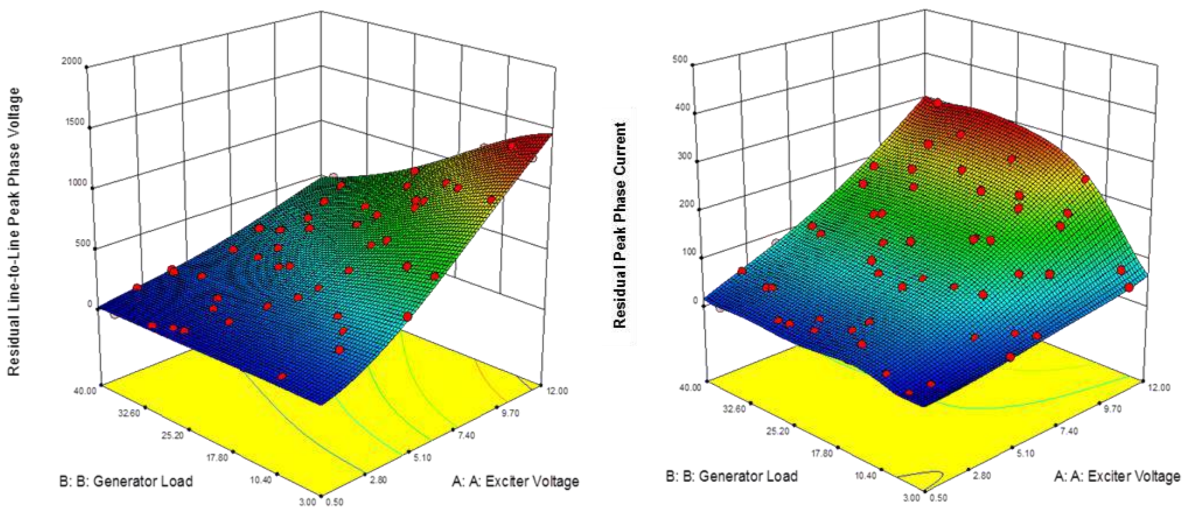


Figure 10. Design space residual maps for generic generator model and experimental results; line-to-line peak phase voltage and peak phase current.

Normally, the generator output is controlled to be a constant 115Vrms at 400Hz. Since both the generic physics-based generator model and the experimental tests were performed without a generator controller, one can use the surrogate polynomials to determine the output generator load and load current as a function of exciter voltage. Figure 11 shows both the output generator load, kW, and load current, Amp, for a constant 115Vrms (282V line-to-line peak phase voltage). Data shown in Figure 11 consist of the uncorrected generic physics-based generator model results, experimental test results, and residual map correction from the generic generator physics-based model to the experiment.

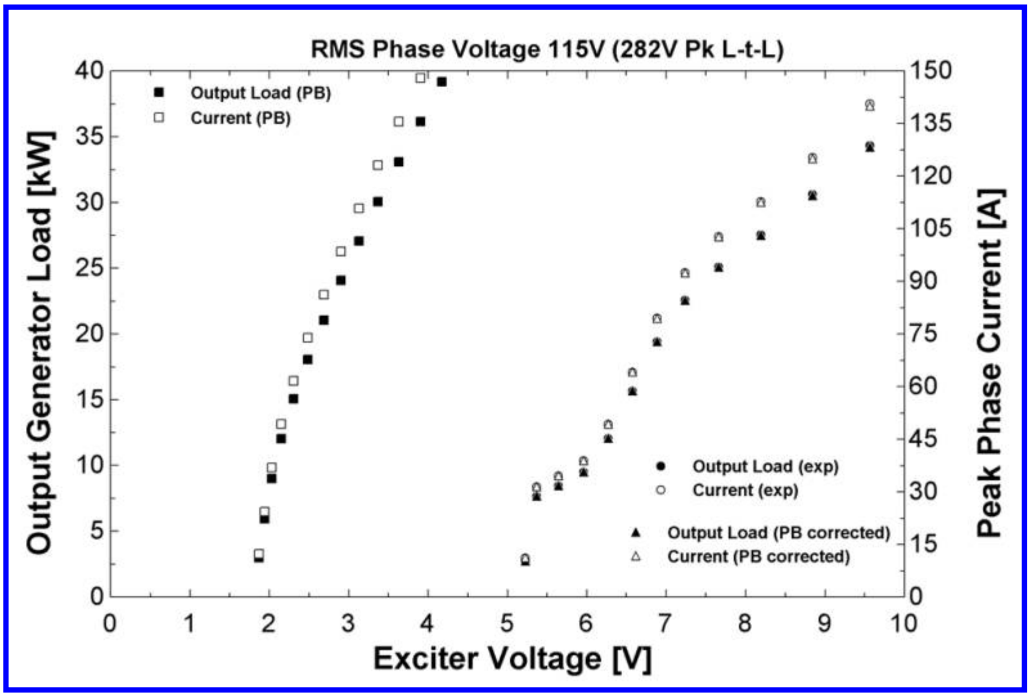


Figure 11. Residual map correction for generic generator physics-based model to experiment at a controlled voltage of 115V (282V line-to-line peak phase voltage).

IV. Vehicle Validation Testing

A. Background

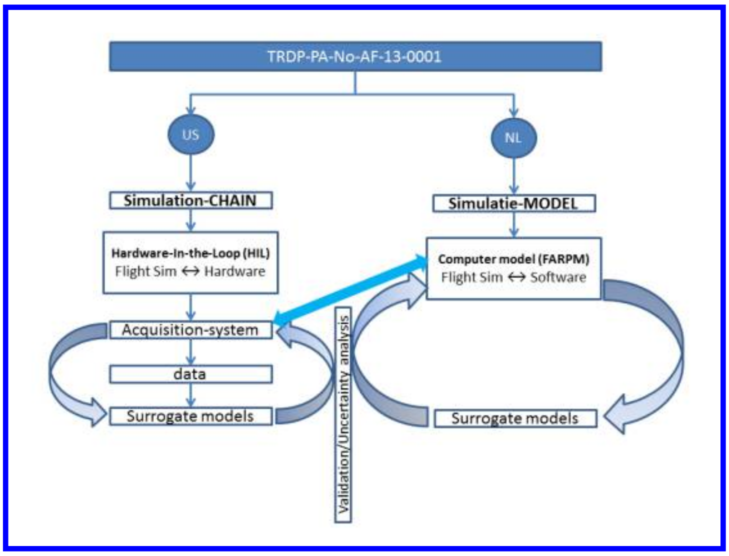


Figure 12 Vehicle validation testing concept.

In the vehicle validation testing concept within the IEPM cooperation AFRL is setting up a simulation chain based on hardware in the loop. AFRL is using two airframes, one originating from the Netherlands and one from the U.S., to be connected to flight simulators and equipped with data-acquisition systems to acquire data from the onboard systems while the aircraft is flown fixed to the floor, using external power. NLR is working on a computer simulation model of a legacy aircraft, in which all onboard systems are also connected to a flight simulator, that drive the boundary conditions for the onboard systems. The hardware in the loop and the computer simulation model approach are compared by the application of a validation and uncertainty analysis in which the surrogate models originating from either approach can be compared and exchanged to improve the computer simulation models. Setting up the computer simulation model is the starting point for the design of the data acquisition system. For the validation of the flight mechanical simulator that drives the internal aircraft system components of the computer simulation model NLR can make use of flight data from the official RNLAF high-demo flight. The advantage of this data set is the fact that the same set of maneuvers is performed by the same pilot in the same aircraft over more than 50 flights per annum, making this data set useful for statistical analysis.

B. Vehicle Simulation Model

The complexity of developing a robust heat and power management simulator due to the many systems and system components in a generic aircraft definition implies the subdivision of the problem in smaller lumps to keep overview of and to maintain momentum in the development. In the current development phase, a two-step simplifying approach has been applied[5].

At first, the flight mechanical part of the simulation, air vehicle system (AVS), has been decoupled from the actual heat and power management simulator (HPMS), Figure 13. This step implies that the driver delivering the inputs for the internal aircraft components can be validated on its own, and that the HPMS follows its own verification and validation track. Ideally, aircraft systems status and output would feed back into the AVS system which is to be expected in the future when validation of models for aircraft components has reached a sufficient level of sophistication.

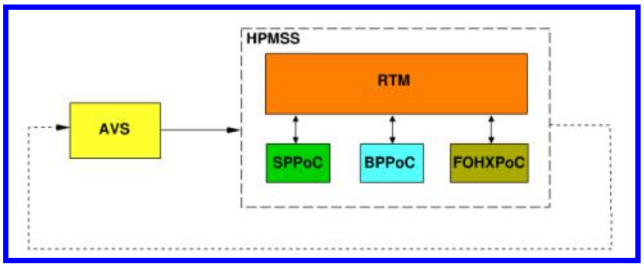


Figure 13. Decoupling of flight mechanical part of the simulator from internal heat and power management system components; feedback of system/component status and outputs is foreseen for the future.

Secondly, the variety of aircraft subsystems has been clustered into a limited number of main sets of systems. After reviewing the aircraft systems playing a significant role in the global heat balance[6], the following four larger subsystems were defined for a generic aircraft that, when combined together, form a top-level architecture for a heat and power management simulator. These larger subsystems under consideration are based on different principles of heat and power exchange and are characterized by:

1. A mechanical drive train subsystem, here known as Shaft Power Proof-of-Concept model (SPPoC);
2. A bleed air subsystem, called Bleed air Power Proof-of-Concept model (BPPoC);
3. A fuel/oil heat exchange subsystem, or Fuel-Oil Heat eXchange Proof-of-Concept model (FOHXPoC);
4. A conductive airframe subsystem, indicated as Reduced Thermal Model (RTM).

The latter subsystem also defines an interface with the environment apart from ram air and engine air flow, including heating of the aircraft by solar irradiation[7]. The subsystems are indicated as proof-of-concept models, mainly because initially it was planned to create four separate models in Simulink to prove their viability and operation. The four subsystems were defined in schematic form on paper as the research into each subsystem necessitated reflection on essential system components and their interconnections. However, after the first proof-of-concept model SPPoC had been achieved in a Simulink environment and realizing how much the four proof-of-concept models interact with each other, it was decided that the logical way forward of modeling required the integration of all envisioned proof-of-concept models into one top-level overall system architecture.

Because the flight mechanical part of the simulation, AVS, has been decoupled from the actual heat and power simulator, see Figure 13, the validation process for the AVS is also separated from the actual heat and power simulator. The validation process for the AVS is based on actual flight data of the official high-demo flight of the RNLAF.

C. Initial Flight Test Data Statistical Analysis

The objective of the initial flight test data analysis is to develop a statistically-based analysis methodology that demonstrates the transformation of position-to-acceleration and then reversing the transformation from acceleration-to-position. The process is modular such that any portion of the transformation may be used as the starting point for future analyses. This will be useful in providing the basis for denoising and smoothing operations that will be employed as the bridge for developing a “statistically-based flight profile.”

The flight data selected for analysis is from actual flight data of the official high-demo flight of the RNLAF. This data is available in coded format, which normalizes and non-dimensionalizes the data, as well as dimensional format. The initial methodology for analyzing this data begins with a theoretical zoom profile that emulates the “vertical climb” or “90° lion climb” portion of the high show, Figure 14. After verification of the numerical implementation of the process, it is applied to actual flight data for one demonstration show as the basis for analyzing the remaining 50 flight demonstration data sets.

The importance of verification is stressed in terms of identification of the source of errors as well as quantification of residuals relative to expected results. In order to perform error analysis, an analytical solution is required. The process developed was then applied to actual flight data. First using coded data (normalized and non-dimensionalized) and then using actual flight data in physical units. With the overall process described, verified, and implemented, it will need to be modified and extended to include the effects of noise-reduction and smoothing. This will enable the process to be used for any type and source of data and to be generally-applicable. There are many challenges in performing this work including selection of the myriad of types of noise reduction as well as smoothing techniques available. It is intended to provide a methodology that automatically detects and selects that best technique for a given and arbitrary data set. This will have direct application in the definition of both flight test and laboratory test data management for future integrated testing which will incorporate flight environment simulation combined with a “tunnel-in-the-sky” concept to evaluate uncertainty quantification (UQ) and propagation (UP).

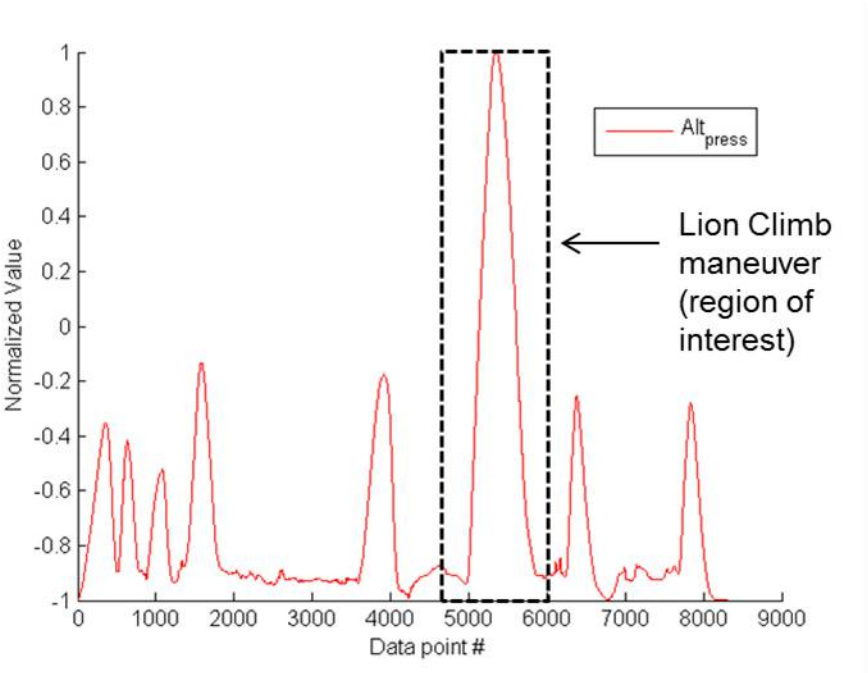


Figure 14. Normalized pressure altitude for a typical high show.

D. "Tunnel-in-the-Sky"

Progress has advanced to the point where the RNLAF high-demo flight can now actually be reproduced by flying the AVS through an indicated first version of a "tunnel-in-the-sky" using a pilot-in-the-loop. The set-up of flying the AVS through a "tunnel-in-the-sky" is shown in Figure 15. The on-screen indicated "tunnel-in-the-sky" is based on flight test data recordings of high-demo flights performed during a high-demo flight. This flight test data are processed high-demo data acquisition recordings in terms of averages and standard deviations. This allowed the reproduction of a series of flown maneuvers with acceptable accuracy, thereby generating and registering more data along the flight path than those recorded, in the actual flights, by the flight test data acquisition system. The resulting larger set of data along the flight path generated by flying the AVS through the tunnel-in-the-sky is of importance to drive the HPMS and thus to gain insight into internal heat and power distributions with time for the associated flight profile.

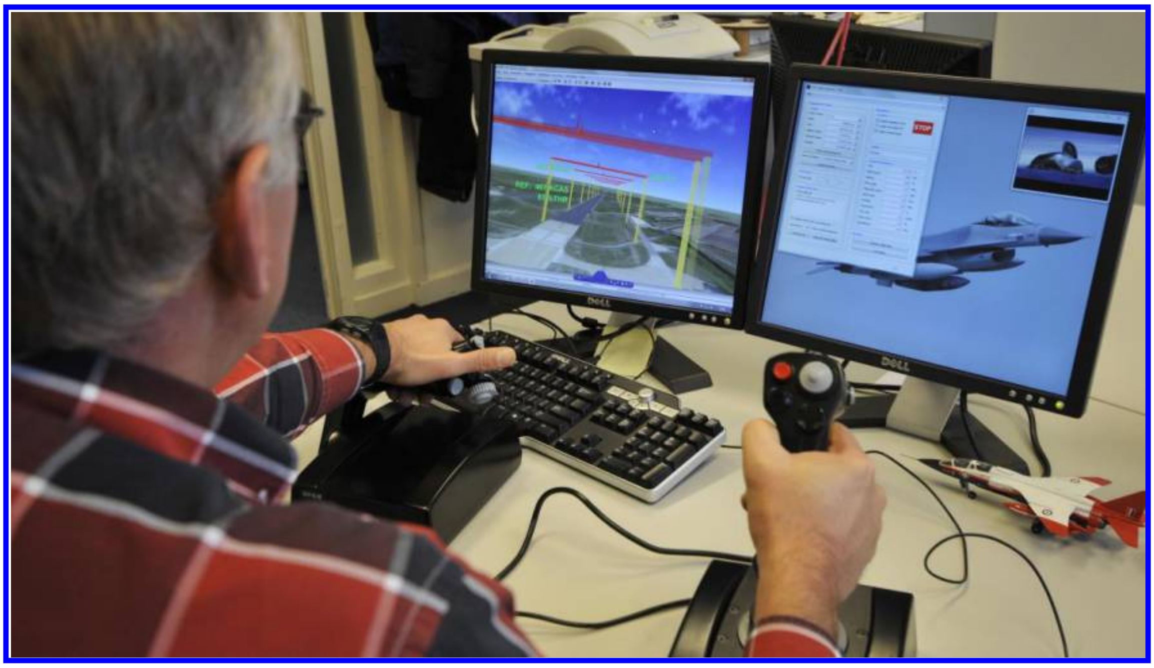


Figure 15 Set-up of a RNLAF high-demo flight by simulated flying through the associated "tunnel-in-the-sky."

The "tunnel-in-the-sky" is not a new concept for flight path visualization; it is rather common for research into novel approach paths for airliners to an airfield. To indicate the complex figures flown by a fighter aircraft in an airshow, some cues that are not normally part of a tunnel in the sky were added to implementing the "tunnel-in-the-sky" concept. By giving the tunnel markers (or frames) the desired yaw, pitch and roll of the aircraft, maneuvers such as knife-edges and barrel rolls were made more obvious. To clearly indicate quick rolls, the top side of the tunnel has a different color and a protruding feature, see Figure 16.

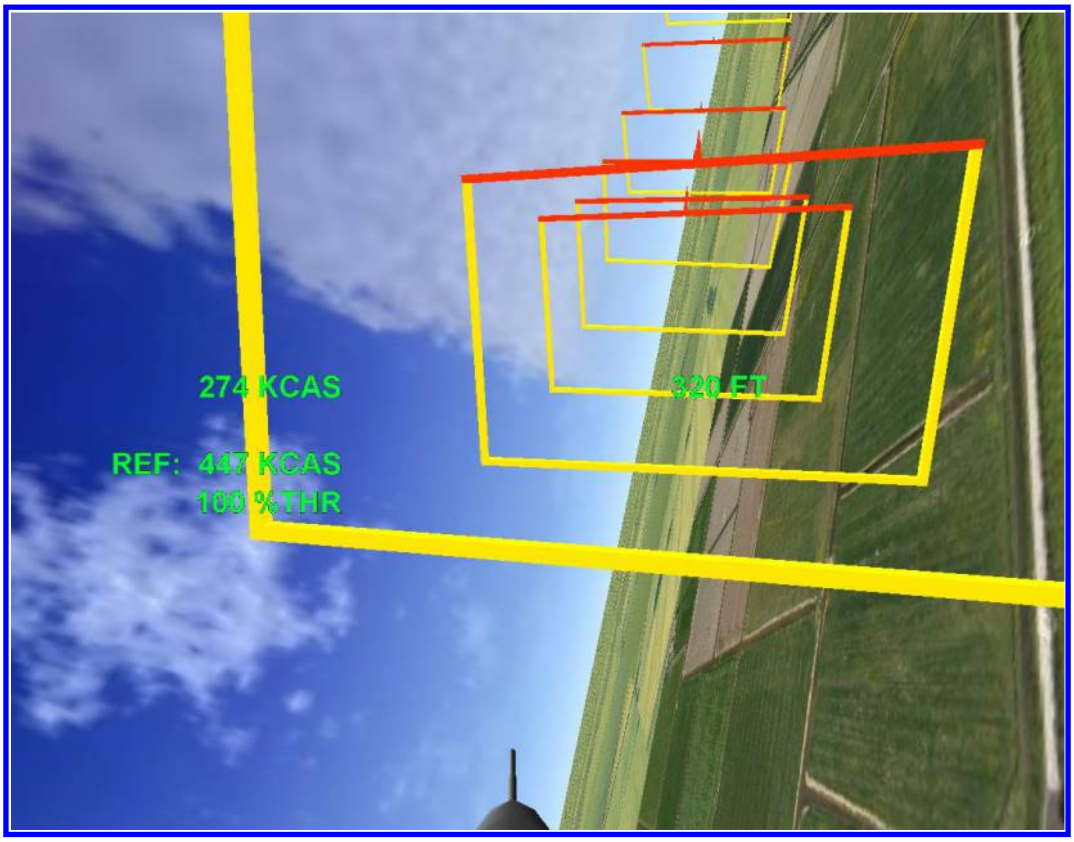


Figure 16 Tunnel in the sky and HUD showing a tight turn. The red side of the tunnel markers indicates 'up' direction in the aircraft body frame. On the bottom left of the HUD, the airspeed and throttle position used during the original flight are shown for reference.

As such, the "tunnel-in-the-sky" is a measure of quality for simulated flights. If the "tunnel-in-the-sky" can be followed within accuracy bounds, the simulated flight data are regarded as sufficiently reliable and can be applied for verification and validation activities. By incorporating advanced statistical data methodologies, the "tunnel-in-the-sky" concept blended with statistically-base flight will allow for the proper accounting of UQ and UP throughout the simulated flight. The comparison of selected data analyses and resulting "tunnels-in-the-sky" will also form a unique capability to properly account for UQ and UP in a "hardware-in-the-loop" (HIL) test environment such as in the Integrated Energy and Power Management (IEPM) Laboratory.

E. Integrated Energy and Power Management (IEPM) Laboratory

As shown in Figure 17, the IEPM Laboratory hosts two airframes (a USAF airframe and a RNLAF airframe), data acquisition, and a simulation cockpit(s). Neither the U.S. nor the Dutch vehicles have the turbine engines; however, the U.S. airframe is a fully configured vehicle with all of the vintage subsystems intact. The turbine engine in the U.S. airframe will be simulated using a high-speed motor drive to simulate the power take off (PTO) shaft of the turbine engine to drive the auxiliary gear box. The Dutch airframe is partially configured with the electrical distribution system and the thermal management portion of the power, electrical distribution, and thermal management backbone with the flexibility to upgrade power and thermal loads to evaluate growth management concepts as compared to a vintage stock airframe.

The IEPM Laboratory assets will be utilized conduct research in defining model-based engineering concepts coupled with growth management to effectively assess the feasibility of potential upgrades and subsequent capability margins for future operations and platforms. These approaches are also expected to assess and define life-cycle operational support requirements for future high power aircraft architectures. Component testing combined with both airframes provide a component to subsystem to vehicle path to define approaches to formulating and evaluating validation testing concepts. The objective of the IEPM Laboratory is to integrate the flight environment simulation with the airframes and “hanger-fly” the subsystems through pilot interaction using either a traditional simulation cockpit or the actual airframe cockpit, Figure 18. A computational, hardware, and software approach was developed and implemented by Protobox, LLC with sufficient expansion capability to integrate the two airframes into a common flight simulated environment. Figure 19 depicts the dynamic validation testing approach coupling the modeling to the airframe and simulator. Independent component and system model runs can be performed concurrently to airframe “hanger-flights” in order to identify and define transient model uncertainty and prediction capability requirements.

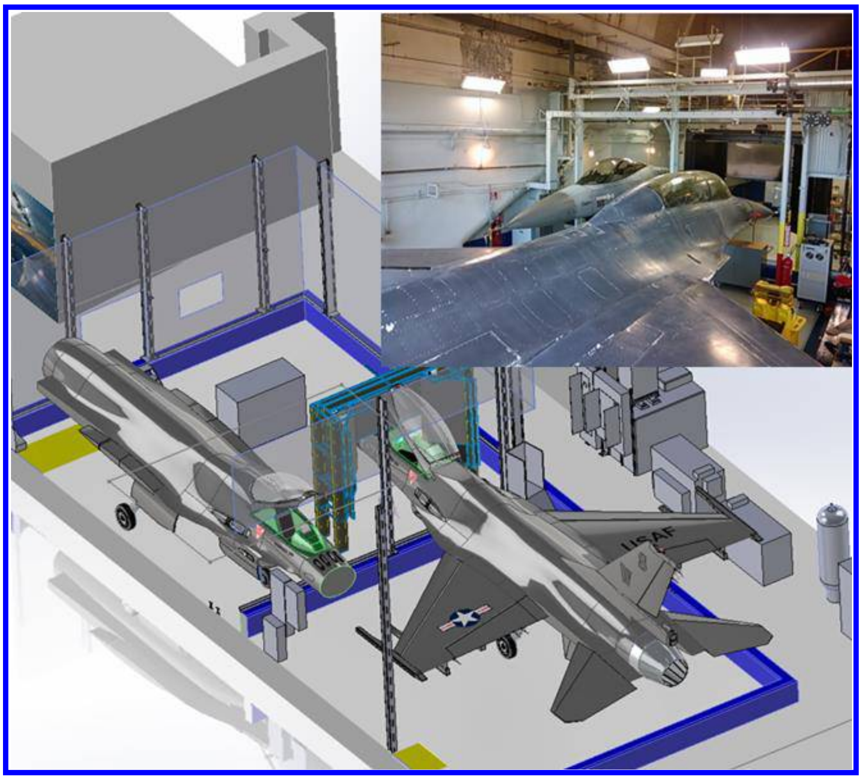


Figure 17. IEPM Laboratory showing placement of both USAF and RNLAF airframes.

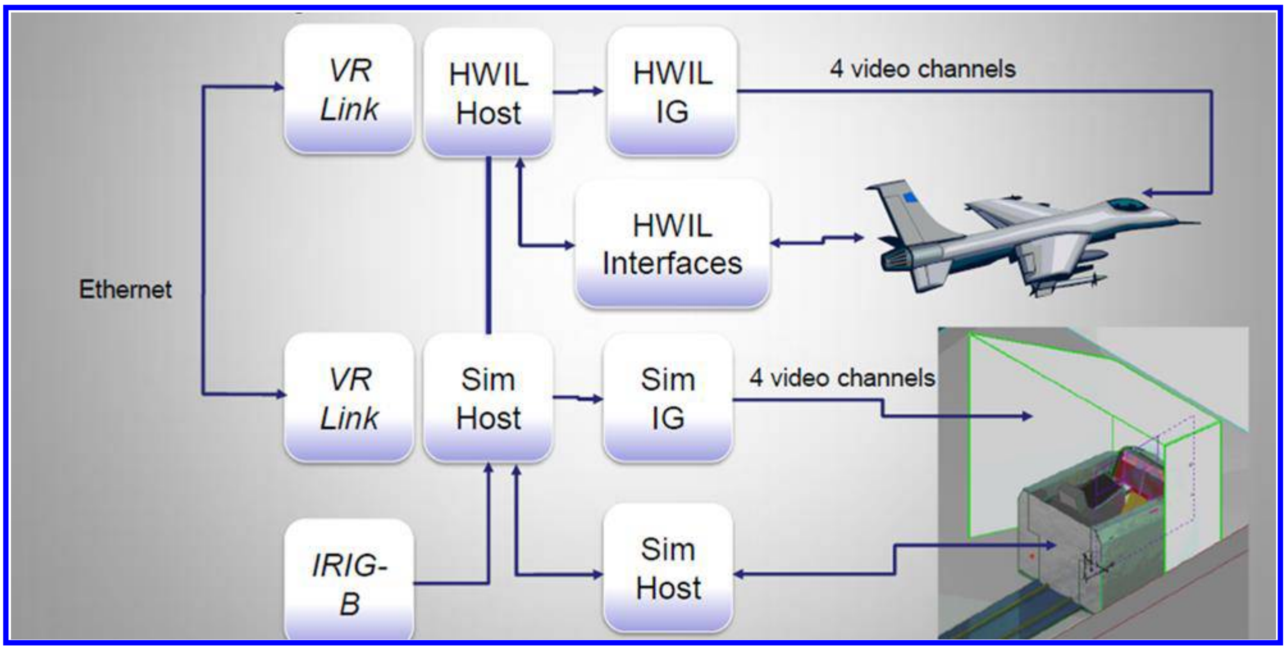


Figure 18. Integration of the airframes and the flight simulation computational hardware developed by Protobox, LLC.

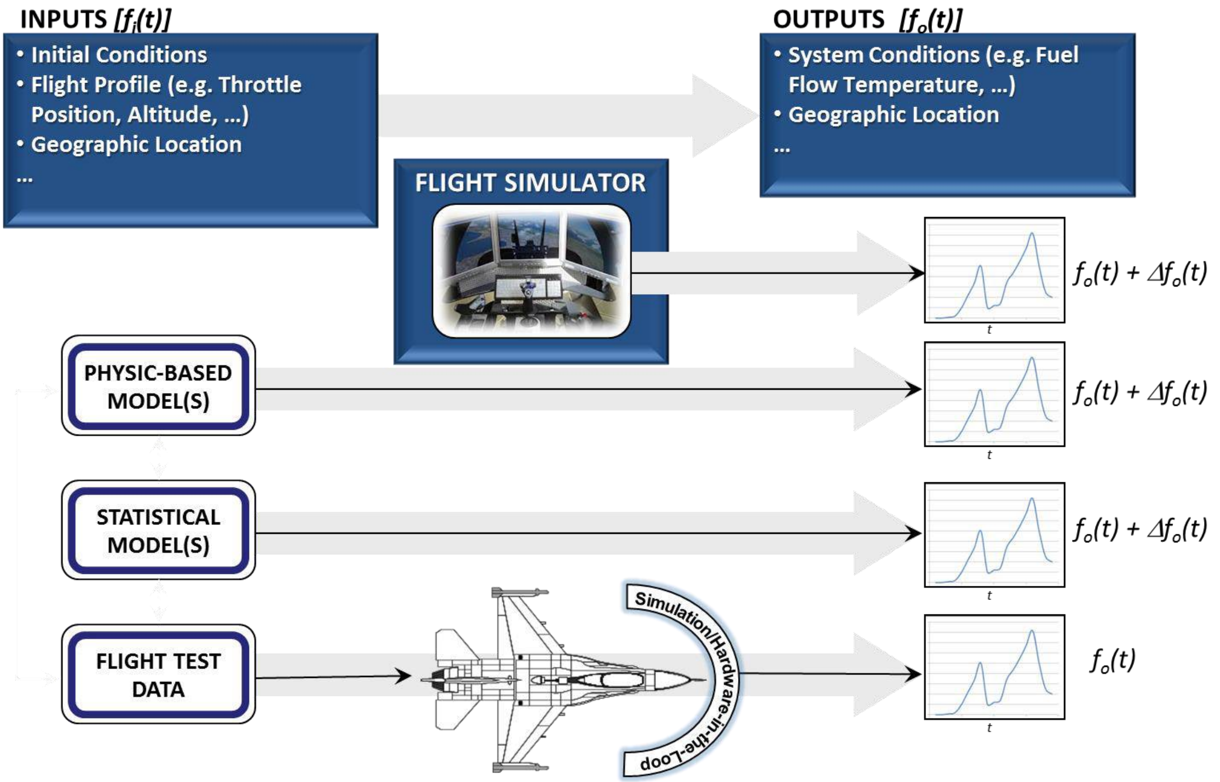


Figure 19. IEPM Laboratory validation testing approach.

V. Conclusion

Validation testing for aerospace vehicles is a key component in the demonstration of a robust coupled model-based engineering and growth management process. Well posed M&S and validation testing can also be envisioned with a view toward design feasibility and evaluation of the future growth potential of the electrical system loads. The impact on the power, electrical distribution, and thermal management backbone coupled to the air vehicle structure and engine can then be effectively assessed. Furthermore, since these backbone components are integrated with electrical system loads and aircraft subsystems, their effective integration can be determined properly as a complex interaction of dynamic loads. It is concluded that experimental data of individual system component tests are not alone sufficient. Laboratory tests on an integrated airframe with interacting subsystems are needed to properly define requirements for effective validation testing and to support a well-posed validation testing approach. These approaches are also expected to offer insight in the definition of life-cycle operational support requirements for future high power aircraft architectures.

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