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Scope, objectives and international dimension of a dynamic aircraft robust power management programme

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Executive summary

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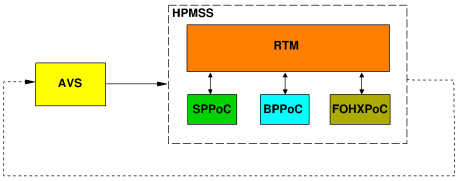

Problem area
With the current generation of legacy aircraft, operations as well as avionics system upgrades are limited by available power and cooling capabilities. During its life time, the operational and functional envelope of an aircraft is updated several times by adding new and more powerful avionics. A new avionics system generally requires more electrical power than before and thus:

1. poses a larger demand on the electrical power system and generator;
2. dissipates more power into heat loads;
3. requires thermal balancing by cool air, posing a larger demand on the environmental control system.

As such, a change in one system implies a chain reaction of variations in operational loads of other systems. Thus, increased thermal loads for proposed upgrades to legacy aircraft will further exacerbate the thermal imbalance of current systems. A more capable thermal analysis is therefore required in order to better understand the impacts of these additional thermal loads. The thermal analysis system is intended to provide ways for robust heat and power management, in particular to support the decision processes regarding acceptable operational capabilities and system upgrades.

Description of work
The work involved in this paper consists of developing a generic top-level architecture for a heat and power simulator of a legacy aircraft, consisting of four major interacting subsystems:

1. the mechanical drive train, using shaft power to drive components;
2. the bleed air circuit to feed the environmental control system;
3. the fuel/oil heat exchange circuit to cool several hydraulic and engine oil flows;
4. the conductive airframe, interacting with all the heat loads on components in the aircraft.

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Time-dependent inputs for the heat and power simulator along a specified flight path are provided by the air vehicle system AVS. AVS is a flight simulator generating sufficiently detailed output data to run the heat and power simulation. The development of the top-level architecture as well as the four major subsystems has been undertaken in an international cooperation with the Air Force Research Laboratory AFRL. Setting up and facilitating the international cooperation is part of the planned work in this programme. The benefits and added value of the international cooperation are found in maximizing the usage and examination of available data, expertise and models. Furthermore, initial verification and validation activities of several components and subsystems has been undertaken.

Results and conclusions

The scope of the programme is to support the decision processes regarding acceptable operational capabilities and system upgrades. Its objectives are to develop the identified missing system and component elements to achieve a realistic level of heat and power management simulation.The status of development of each of the above mentioned subsystems is outlined, their implementation in a Simulink environment is addressed, and ways for verification and validation of the developed approach are described. Some results of initial verification and validation activities are shown on engine, hydraulic power actuation system, and AVS. The cooperation in an international consortium with AFRL has led to a balanced view on, and maximized usage of, theoretical models, experimental data, and surrogate models derived from both. Three levels of experimental testing are deemed important for a full verification and validation of the heat and power simulator: component testing under controlled conditions, interacting systems testing in an accessible ground test facility, and flight testing to get a data set under actual operational conditions.

Applicability

This paper outlines the intermediate status of an active research programme. The addressed heat and power management simulator is progressing towards a fully operational version. For actual applications to a particular airframe, the generic set-up of the simulator needs adjustments to conform to the specifications of that airframe. For that purpose, a large amount of system information will be required. The application of the heat and power management simulator is initially intended to maintain and assure a valid operational state of legacy aircraft during their remaining life time, although the application to future new aircraft is inherently possible.

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Summary

In this paper, the technical and organizational structure of a dynamic heat and power management research programme is outlined. This programme is aiming at the development of a generic heat and power management simulation system. With the current generation of legacy aircraft, operations as well as system upgrades are limited with respect to available power and cooling capabilities. To support maximum operational performance during the remaining life time of legacy aircraft, a reliable power management simulator enables the assessment of capability margins for operations and upgrades. The simulator is also expected to offer operational support capabilities for future all-electric aircraft. As a demonstration of the selected approach for power management modeling, the examples in this paper comprise modeling and validation of the electrical generator, the hydraulic system, and the engine. Since these components are not stand-alone devices in the aircraft but involve fluctuating loads due to pilot action involving aircraft control commands and other systems being switched on and off, their multidisciplinary complexity is taken as example. A reflection of this complexity has to be included in the modeling as well as in the verification and validation process of the simulator, requiring test data at different levels. It is concluded that experimental data of individual system component tests are not sufficient; laboratory tests on an airframe with interacting subsystems as well as flight tests are needed for validation. In turn, the heat and power management simulator is expected to support the definition of test data to be acquired. The international cooperation, instrumental to maximize the use of available test data, generic models, and expertise, is addressed.

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Scope, Objectives and International Dimension of a Dynamic Aircraft Robust Power Management Programme

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In this paper, the technical and organizational structure of a dynamic heat and power management research programme is outlined, aiming at the development of a generic heat and power management simulation system. With the current generation of legacy aircraft, operations as well as system upgrades are limited with respect to available power and cooling capabilities. To achieve maximum performance for the remaining life time of legacy aircraft, a reliable power management simulator supports the assessment of capability margins for operations and upgrades. The simulator is also expected to offer operational support capabilities for future all-electric aircraft. As a demonstration of the selected approach for modeling, the examples in this paper comprise modeling and validation of the electrical generator, the hydraulic system, and the engine. Since these components are not stand-alone devices in the aircraft but involve fluctuating loads due to pilot action involving aircraft control commands and other systems being switched on and off, their multidisciplinary complexity is taken as example. A reflection of this complexity has to be included in the modeling as well as in the verification and validation process of the simulator, requiring test data at different levels. It is concluded that experimental data of individual system component tests are not sufficient; laboratory tests on an airframe with interacting subsystems as well as flight tests are needed for validation. In turn, the heat and power management simulator is expected to support the definition of test data to be acquired. The international cooperation to maximize the use of available test data, generic models, and expertise is addressed.

Nomenclature

ADG	=	Accessory Drive Gearbox
AFRL	=	Air Force Research Laboratory
AVS	=	Air Vehicle System
BPPoC	=	Bleed Power Proof-of-Concept model

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CSD = Constant Speed Drive
ECS = Environmental Control System
EGB = Engine Gear Box
EPS = Electrical Power System
FMS = Fuel Management System
FOHXPoC= Fuel-Oil Heat eXchange Proof-of-Concept model
HPAS = Hydraulic Power Actuation System
HPMSS = Heat and Power Management Simulation System
IDG = Integrated Drive Generator
NLR = National Aerospace Laboratory
NTP = National Technology Project
PA = Project Agreement
RNLAF = Royal Netherlands Air Force
RTM = Reduced Thermal Model
SPPoC = Shaft Power Proof-of-Concept model
TERTS = Turbine Engine Real-Time Simulator

I. Introduction

WITH the current generation of legacy aircraft, operations as well as avionics system upgrades are limited by available power and cooling capabilities. This compact problem statement comprises a world of heat and power challenges. For clarification, suppose an aircraft has an electrical generator which is on the average loaded close to its maximum capacity. Changing the envelope of operations of the aircraft by the replacement of legacy avionics systems or the introduction of additional equipment then becomes problematic if the electrical power demand in the new situation exceeds the maximum electrical power capacity. To solve this situation, either the entire electrical power generation system needs to be upgraded, or a robust time-sharing strategy is needed to operate the aircraft in such a way that the available electrical power is automatically directed to those systems that are essential for the flight phase at hand. Furthermore, as all aircraft systems have an overall efficiency smaller than one, each system dissipates part of the delivered power into heat. The generated heat has to be removed from the aircraft. For electrical systems, usually cool air is used for avionics bay conditioning. All distributed heat sources in the aircraft pose a significant demand on the cooling system. Replacement of legacy aircraft systems by newer ones is not an a priori guarantee for improvements in system efficiency. Furthermore, the total power demand usually increases during the operational life time of an aircraft. An increase in overall power demand implies a larger amount of heat dissipated in the aircraft, and thus a higher demand for cooling. The rate of increase in heat transfer efficiency is not likely to keep pace with the rate of change of overall thermal loads. It remains to be seen whether the legacy cooling systems can cope with the increased thermal loads of the upgraded systems.

Increased thermal loads for proposed upgrades to legacy aircraft will further exacerbate the thermal imbalance of current systems. A more capable thermal analysis is therefore required in order to better understand the impact(s) of these additional thermal loads. Moreover, the thermal analysis system is supposed to provide ways for robust heat and power management, i.e. to support the decision processes regarding acceptable operational capabilities and system upgrades. A robust heat and power management simulator should be capable of indicating the margins of use of heat sinks in the aircraft (usually outside air, fuel, and airframe structure) within operational limits for temperature. The focus for the development of the heat and power management simulator is on legacy aircraft because verification and validation of the simulator requires a well known and fully understood data set which is available or can be obtained on legacy aircraft. However, it is anticipated that for future all-electric aircraft the need for a heat and power management simulator will be of even higher importance. Also, it is expected that the growing use of composite materials in new generations of aircraft significantly impacts the heat sink and heat dissipation behavior of the airframe, while also the larger thermal sensitivity of deterioration of the composite materials as opposed to metal designs come into play.

Aircraft thermal problem analysis has attracted an increasing amount of attention over the past few decades[1-5]. This is not only recognized for military aircraft but is also addressed in a growing number of studies for civil aircraft[6,7]. The main heat sources in an aircraft obviously are the engine and the avionics systems. For cooling, the fuel capacity on board provides a large heat sink, while also engine bleed air or ram air is often used locally. Due to the multiple heat exchanges between aircraft subsystems, e.g. between engine or hydraulic oil and fuel, air and fuel, and between the heated fuel or air and the airframe, the overall complexity of an aircraft heat model and power management simulator should not be taken lightly. In the following, the selected approach for the development of a dynamic aircraft robust heat and power management simulator is outlined.

II. Roadmap towards a robust heat and power management simulator

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.

At first, the flight mechanical part of the simulation (the air vehicle system or AVS) has been decoupled from the actual heat and power management simulation system (HPMSS), see Figure 1. This step implies that the driver delivering the inputs for the internal aircraft components can be validated on its own, and that the heat and power management simulator 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.

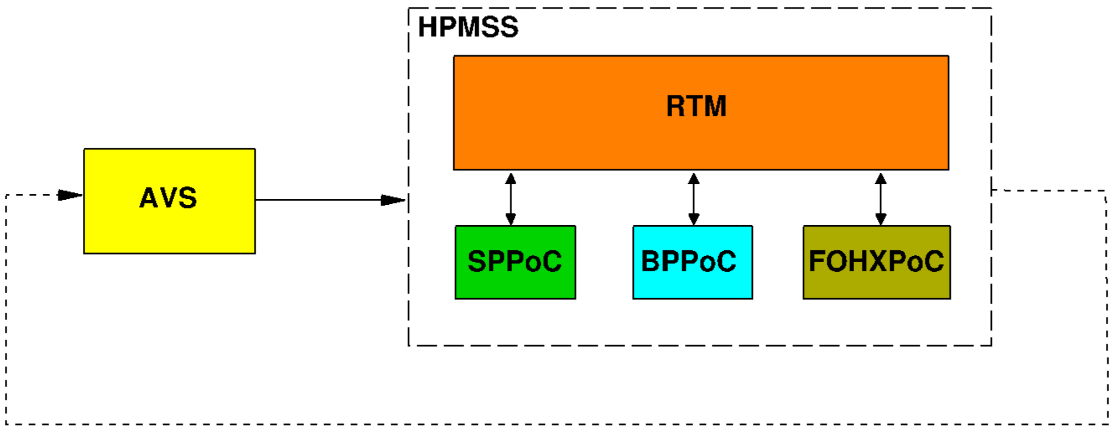

Figure 1. Decoupling of flight mechanical part of the simulator from internal heat and power management simulation system; feedback of system/component status and outputs is foreseen for the future.

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[8], 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, shown in Figure 1, 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[9]. 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.

The shaft power is taken from the engine through an axis driving the engine gear box, which in turn drives the accessory drive gearbox. A schematic representation of the SPPoC model as defined in an early phase of the programme is shown in Figure 2. Here, a central part of the system is formed by the Air Vehicle System (AVS), which is a flight simulator capable of flying prescribed flight paths as defined on the left hand side of AVS and generating the time-dependent data along the flight path, made available in a databus to drive the heat and power simulator. Figure 2 shows the engine providing the power demand for the mechanical drive train through gear boxes to the constant speed drive of the electrical generator and hydraulic pumps. Also indicated in Figure 2 is that the level of modeling of system blocks (here, the hydraulic power actuation system HPAS and electrical power system EPS) is kept as flexible as possible, depending on the specific modeling needs and availability of data and models. Thus, it is anticipated that subsytems can be modeled either as a zeroth-order model (constant input/output ratio, i.e. a linear input/output relation), as a transfer function or database implementation giving a more realistic nonlinear input/output relation on the basis of experimental data, or as a dynamical system based on physical modeling principles.

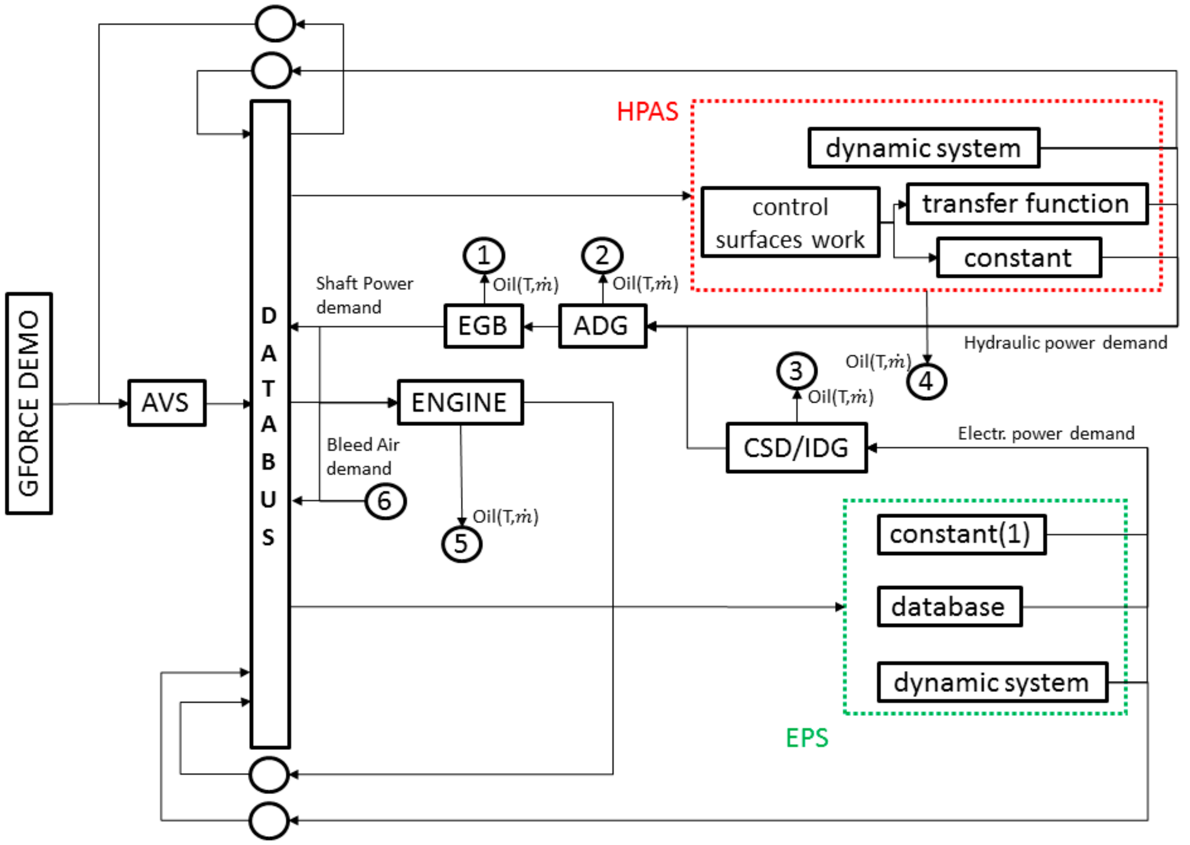

Figure 2. Schematic representation of early development phase of SPPoC model.

Bleed air is obtained from the engine compressor stages, and can be used for various purposes depending on the type of aircraft at hand. The main use of bleed air is to provide input air of sufficiently high density and pressure to the environmental control system. The main output of the environmental control system is air at the right properties (temperature, pressure, relative humidity) for either cockpit/cabin air pressurization or for cooling purposes of equipment. A large demand for cool air comes from the electrical power system where avionics bays need cooling capacity to keep bay and thus equipment temperature within operationally acceptable limits. In Figure 3, an early development phase schematic representation of the bleed air power proof-of-concept model is shown.

As remarked earlier, fuel is an important heat sink on board of aircraft. The need to bring large amounts of fuel for propulsion provides a vast cooling capacity for excessive heat, albeit within reasonable limits in order to avoid fuel deterioration as well as boiling, affecting the stability of the primary role of fuel as a propellant. The cooling capacity of fuel in most aircraft is used in fuel-oil heat exchangers, either to extract heat from engine or other system components oil or hydraulic oil. A schematic view of an early development phase fuel-oil heat exchange proof-of-concept model is given in Figure 4. Here, it is envisaged that engine oil as well as engine gearbox oil, accessory drive gearbox oil, hydraulic fluid and the electrical power generator oil are fed through heat exchangers where fuel is used as coolant. Hot fuel from the heat exchangers is eventually used as propellant unless the temperature of the fuel has become too high. In that case, fuel is returned to the fuel tanks for mixing with cooler propellant.

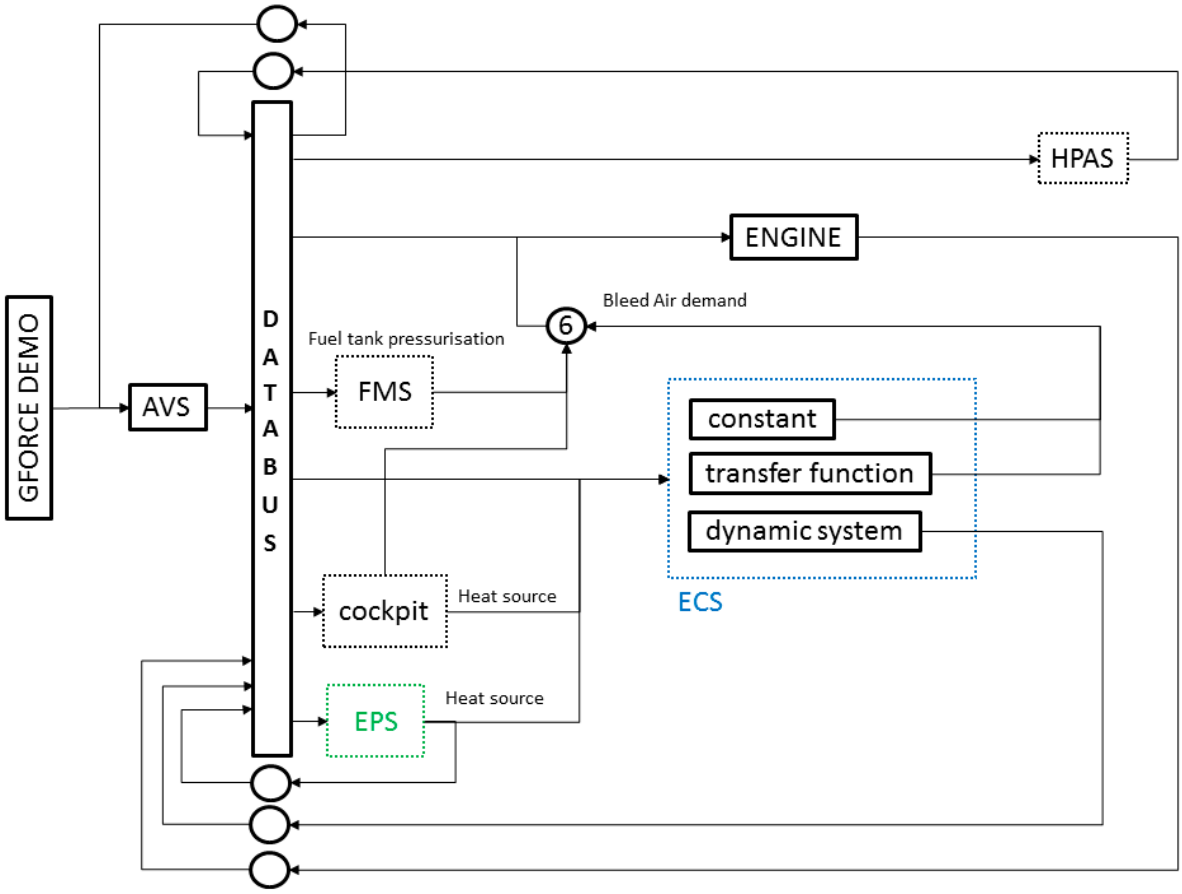

Figure 3. Schematic representation of early development phase of BPPoC model.

The fourth large subsystem, i.e. the airframe, is an obvious heat sink. It receives heat from the aircraft systems in many places, e.g. in the engine bay area, through fuel tanks where heated fuel is mixed with cooler propellant, in avionics bays where electrical equipment radiates heat, through hydraulic and fuel pumps, or by external influences like solar irradiation. Thus, the heat connection of the airframe with the subsystems described above takes place everywhere a source of heat is found. In this sense, the airframe forms an additional layer on top of the other three subsystems with many interactions with all system components, see Figure 1. An airframe consists of many bays and the heat transport within bays can be made up of conduction, convection or radiation. The heat exchange between bays is mainly through conduction in the airframe, unless a convective heat path is explicitly defined in the airframe. The form in which the airframe as heat sink is modeled is currently under investigation[10]. A thermal package seems appropriate to arrive at a well-defined nodal reduced thermal model, although the choice of package should not disable the required interaction with the other subsystems within a Simulink environment. Thus, a thermal package offering export options to arrive at the RTM in an independent form for inclusion within Simulink might be the preferred choice.

For the purpose of developing a feel for challenges and difficulties that might be encountered in the selected modeling approach, the SPPoC system has been worked out in a Simulink environment, see Figure 5. Using zeroth order models in the system blocks, apart from the engine block where a relatively detailed physics-based model was used, a working simulator has been achieved even though many details were set at guessed values. The SPPoC simulator responds in a realistic way to the flight path data of the prescribed maneuvers, which is in part enforced by using a very realistic engine model. The interaction between system blocks has been tested in this proof-of-concept simulator approach, e.g. by having not only a driving shaft speed from the engine to the engine gear box but also a variable thrust power loss of the engine due to the fluctuations in required shaft power during different flight phases.

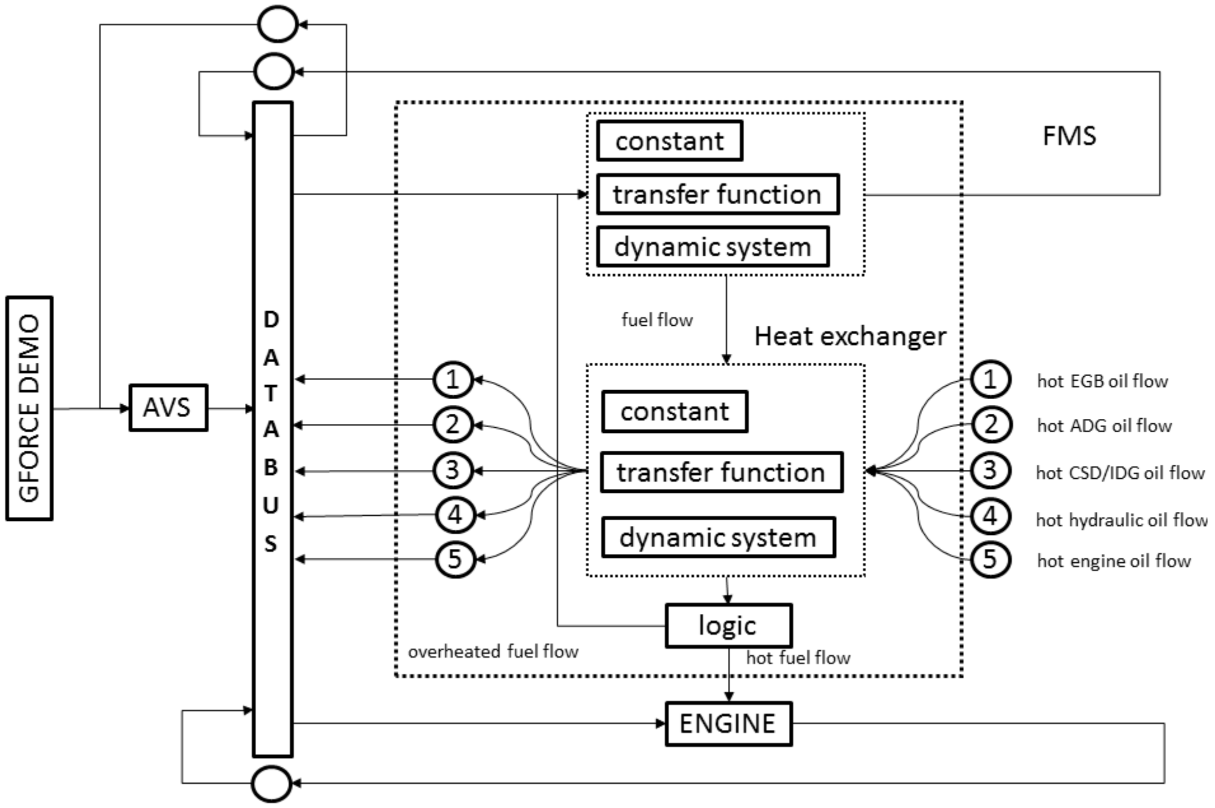

Figure 4. Schematic representation of early development phase of FOHXPoC model.

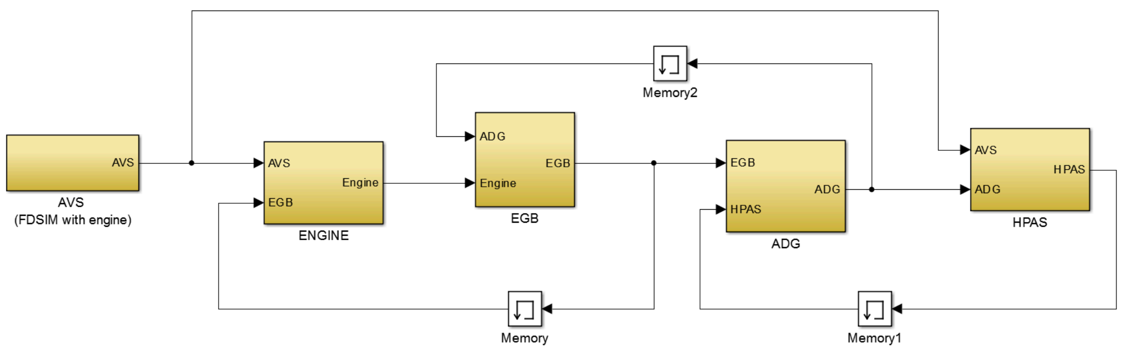

Figure 5. Early development phase shaft power proof-of-concept model (SPPoC) implementation in Simulink.

As remarked, the isolated development of the other proof-of-concept models within a Simulink environment appeared to have less benefits due to the highly entangled interactions between subsystems. The current development is therefore focusing on a top-level architecture including SPPoC, BPPoC and FOHXPoC with provisions for RTM-coupling.

III. Dynamic aircraft robust power management programme

The current programme, on the Netherlands side, started in 2012 as a follow-up of a National Technology Project (NTP) on dynamic aircraft heat and power management that has been active during 2011. The NTP focused on identifying available and suitable models of aircraft systems for heat and power management and listed the missing bits and pieces required for a power management simulator. The objectives of the current programme are to develop the identified missing system and component elements to achieve a realistic level of heat and power management simulation and thereby to ultimately increase the operational capabilities of existing legacy, evolving, and future aircraft by establishing the impact of operational choices on missions and by optimization of flight paths.

Initial work in the programme has been aiming at progress towards a working heat and power management simulator from an operator-centered viewpoint. The operator-centered viewpoint indicates that the simulator needs fast turn-around times, employing models at relatively simple or intermediate level of complexity. As mentioned before, three levels of modeling have been identified: a constant or linear relation to link input and output, a transfer function or other surrogate model, or physics-based models.

A bilateral Dutch-US international project agreement (PA) was approved late 2013. The research activities within the framework of dynamic aircraft heat and power management will focus on the consequences of design choices and urgent need for well-posed high-level physics-based modeling.

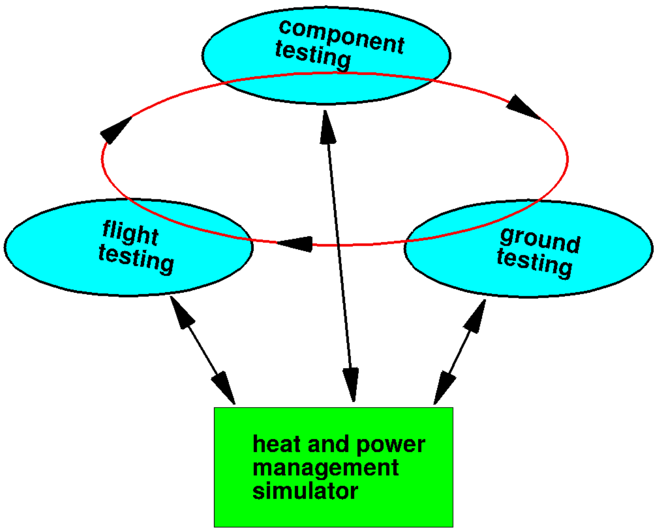

Figure 6. Interrelations between power management modeling (simulator) and testing for validation data; necessary tests comprise component testing, ground testing of interacting systems, and flight testing.

The Dutch focus in this programme is put on the development of a heat and power management simulator including subsystem models for legacy aircraft upgrades and operations assessment. For validation of the modeling, flight test data are submitted to the programme. The US focus is on electrical systems of an all-electric aircraft. Their contribution consists of component and ground testing, surrogate modeling based on experimental data, and physics-based models of specific electrical components.

The introduction of the aircraft designer's viewpoint in the programme implies the need for an innovative way of looking at aircraft design and testing. We believe that existing models and the widely accepted design philosophy of aircraft systems are no longer sufficient to arrive at well-designed new aircraft concepts. The implementation of the all-electric aircraft philosophy, combined with new materials, poses new and poorly understood challenges to the heat and power management in aircraft, having a substantial impact on aircraft system design. For new aircraft concepts, the specifications for subsystems cannot simply be copied from those of legacy aircraft. Specifications reflecting the variety of conditions that subsystems will have to endure in new aircraft concepts are difficult to assess without robust modeling tools. Testing of systems in stand-alone mode is insufficient to fill this gap, as the interaction of systems becomes more and more important for the determination of realistic environmental and operational system loads. More elaborate testing of interacting systems in a controlled laboratory environment (ground testing, possibly on an airframe) is mandatory to gain insight into the mutual influence of system behavior on operational conditions. But even in a controlled laboratory environment, applying appropriate and realistic loads on a component or a few systems is not that easy if knowledge is lacking on actual operational loads and their variations due to interactions. This is where flight tests come in. Flight test data have to fill the gap in the knowledge base for component and system tests on the ground. However, a flying testbed is needed for the execution of realistic flight tests and it should be remembered that even in a flying aircraft not every parameter can be measured in a straightforward way.

So, two important observations evolve here. At first, the knowledge base for aircraft system loads and their variations has to be established on legacy aircraft since a reasonably instrumented flying test bed is needed in the verification and validation process, in combination with isolated component tests to assess component characteristics and ground testing of interacting systems to achieve common knowledge on fluctuations in operational conditions. This process implies that results of component and ground tests dictate the data to be monitored in flight tests. Also, the development of a heat and power simulator for legacy aircraft automatically generates the highly desired capabilities for upgrade implications assessment and optimization of operational usage. Secondly, for new aircraft concepts without a flying testbed available, a validated heat and power simulator using generic subsystem models is required to generate directives for component and ground testing and to fill in the missing flight testing capability. The interrelations of these processes are depicted in Figure 6.

With these observations at hand, the development of a realistic heat and power management simulator is in first instance based on legacy aircraft for which sufficient test data are available or can be obtained. The selected simulator development approach involves a top-level system architecture containing all subsystems and main heat exchange interactions between subsystems. In order to arrive at a working heat and power management simulator, the system blocks are filled with appropriate models for subsystems and components. It is anticipated that, for a manageable simulator with development potential during its application, most of the system blocks will initially be filled with some form of algebraic zeroth-order models. The development of more sophisticated system blocks on the basis of measured data and surrogate models as well as on physics-based models is part of the programme.

IV. Examples of modeling approach

In this chapter, we address the actual modeling activities for three components/subsystems in order to give an impression of the current status of modeling and to further clarify the usage of different levels of modeling. The modeling efforts for the electrical generator in combination with the electrical power system, for the hydraulic power actuation system, and for the engine are described below.

A. Electrical generator

As a first example of modeling an actual component in the present configuration we will address the electrical generator. It is a well-balanced example in the sense that technical status of modeling as well as available experimental data of both cooperation partners are complimentary to each other.

In the current situation, an electrical power system (EPS) is available on the Netherlands side which is combined with a zeroth-order model of a generator. The electrical power system is available in the form of power demand tables of avionics systems and other electrical components such as fuel transfer pumps, and is based on average power usage during operational usage. The dataset includes reactive power to overcome inductances and provides the total electrical power demand at a certain time in flight, based on the active instrumentation and electrical components for that flight segment. As such, the EPS can be considered as a surrogate model or transfer function based on experimental data. The zeroth-order generator model itself is an extremely basic one following some straightforward engineering reasoning: generator effectiveness has been assumed and as long as the total electrical power demand corrected with the generator effectiveness does not exceed the maximum power that can be delivered by the generator it is taken for granted that the power demand is delivered to the respective systems. The non-effective part of the total generator power demand is transferred into heat. Transfer of power into heat is explicitly included within the current top-level system architecture, independent of the level of modeling of system blocks. In the present set-up, the EPS and generator models have no dynamic content.

On the US side, there is no electrical power system available. However, a generator has been modeled on the basis of test bank data resulting from stand-alone component tests under application of different loadings. The set of experimental data has been reworked into a surrogate model[11,12]. At the same time, generic physics-based generator models have been developed using first principles of electrodynamics. Using such high-level physics-based models, simulation data could be generated as well and a surrogate model could be constructed based on the simulated data. A comparison between the surrogate models based on experimental data and on simulated data is then a logical follow-up step. Such a comparison directly includes an appreciation of data uncertainties and modeling accuracy. This subject will be addressed in more detail in the section on verification and validation activities below.

B. Hydraulic power actuation system

One component, characteristic of legacy aircraft, is the hydraulic power actuation system (HPAS) to control the aircraft by movement of the control surfaces. For this particular aircraft the hydraulic pumps are mechanically powered by the engine through the engine gear box and the accessory drive gear box, as shown in Figure 5. If the system is incorporated in a fly-by-wire type aircraft, the HPAS will continuously pass power to the control surfaces and heat the oil, therefore making it necessary to continuously cool the oil through heat exchangers as made visible in Figures 2 and 4. A high-level physics-based model is under development consisting of pumps, integrated servo actuators (ISAs), piping and control surface loads consisting of contributions due to aerodynamics and inertial hinge moments on the control surfaces. The input data required for the computation of the hinge moments, which forms the actual power demand on HPAS, are based on AVS-delivered control surface deflection data from flight mechanical considerations.The model is constructed using the Simulink-related Simscape toolbox Simhydraulics. Usage of such a toolbox provides access to predefined generic actuators, cylinders, pumps, valves, and the like, for which only parameter values have to be identified to mimic a specific application. Attention is focused on correct dynamic behavior of the system as well as power loss in the system and the resulting heating of the hydraulic fluids, HPAS-components and their environment.

C. Engine

For the engine, an in-house development of NLR over a period of many years has formed the basis. The Gas turbine Simulation Program (GSP), a component-based modeling environment, is NLR's primary tool for gas turbine engine performance analysis. The elaborate engine model that is currently in use for simulation purposes is based on a thermodynamic GSP-model employing thermodynamic equations as well as relations for gas mixtures, exhaust gas components, and the like. The GSP-model has been converted to Matlab Simulink for easy linking with other applications, including flight simulators, with specific emphasis on real time simulation capability which required a dedicated time integration approach. This engine model is sometimes referred to as the TERTS-model (Turbine Engine Real-Time Simulator). This engine model is a high-level model based on physical principles per engine component. A more detailed description can be found in Ref. 13.

For the current heat and power management simulator under development, the engine model has been enhanced with dedicated output variables for the heat and power balance of the aircraft. For the currently intended application, specific provisions have been included in the Simulink implementation of the engine model to allow both shaft power take-off and bleed air take-off from the engine, including a realistic response of the engine performance to the demanded levels of shaft power and bleed power. Additionally, engine oil pressure and temperature calculation routines have been included in the engine model, bearing a realistic relation with known engine data. The engine model performance will be addressed in the verification and validation section below.

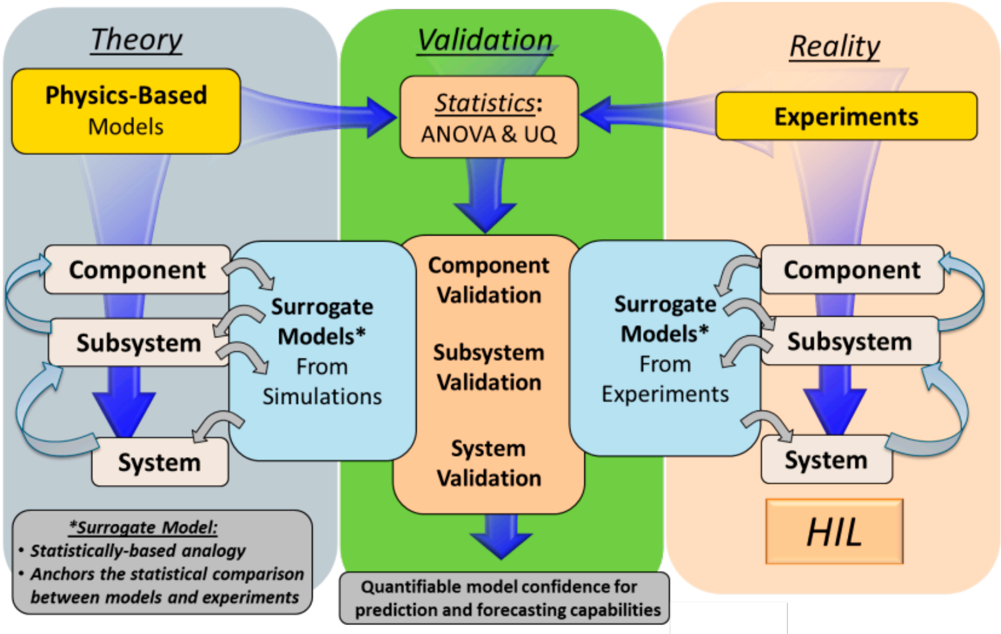

Figure 7. Schematic representation of validation process.

V. Verification and validation activities

As a starting point, the verification and validation activities consist of system component tests that are however insufficient for full verification and validation of interacting models. Additional levels of testing are needed, including the variations in boundary conditions imposed by the mutual interaction of systems. These consist of flight test data from instrumented aircraft combined with laboratory test data on an instrumented airframe. Similarity between flight test and lab test has to be ascertained to be able to combine test data into models and use one set as verification of the other. Test data analysis, interpretation and manipulation procedures are tested or under development to incorporate model uncertainties[14,15,16].

A. Validation philosophy and objective

The overarching validation process used in this effort is depicted in the generic form shown in Figure 7. This validation process can be tailored in order to validate the physics-based model from experimental and/or flight test results. Ideally, the physics-based model is already available to initially define inputs and outputs needed to design and verify a proper statistical model. Using model results, an initial statistics-based surrogate model can be developed. Using an uncertainty quantification approach by taking the total derivative of the surrogate model under development, the experimental and/or flight test plan can be defined and implemented through a Design of Experiments approach.

In addition, stochastic methodologies to evaluate time-variant validation concepts will also be considered as discussed by Fuqua and Doty[14,15]. This requires a fundamental shift in the modeling approach employed by the designers of complex systems of systems – a shift away from deterministic modeling and towards stochastic system analysis and simulation. Stochastic system analysis inherently recognizes the uncertainty of real-world system operation and can be used to model complex systems with multiple noisy, time-varying and state-dependent parameters with their own probability distributions and non-linear factor interactions, across varying domains with consistent measures of merit.

As discussed by Fuqua and Doty[14,15], original data may be used to develop statistical modeling methodologies to anchor validation concepts. In this manner one is able to address the limitations of developing a physics-based, first-principles model. Using these stochastic approaches, one is able to produce an acceptably precise and/or accurate model that best approximates the original data. In such cases, an updated procedure for stochastic model development and parameter estimation based upon data-driven principles will be addressed through the use of randomly-developed training data for demonstration.

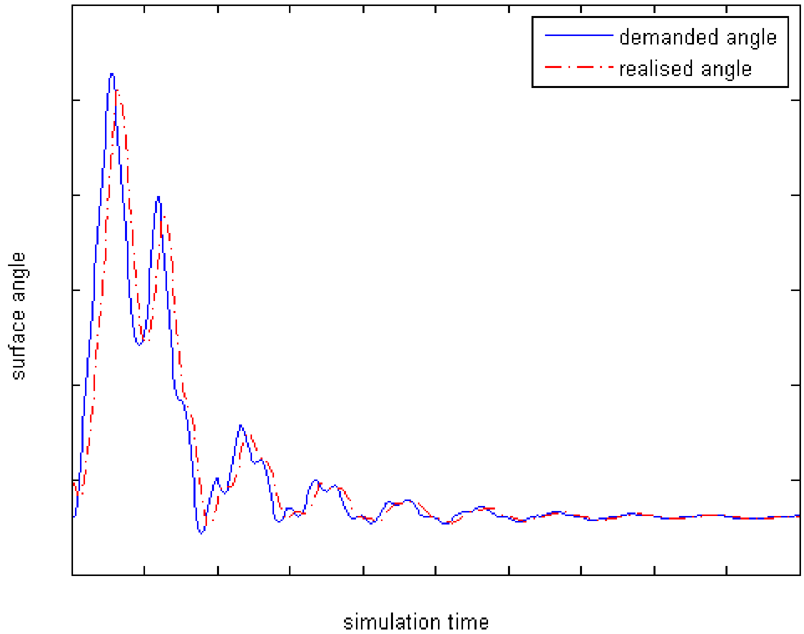

Figure 8. Example of HPAS system dynamical behavior.

B. Initial HPAS physical model verification

The high-level physics-based HPAS system has been scrutinized in terms of response, dynamic characteristics and stability by employing specific time-dependent input to the deflection of the control surfaces in order to move along a specified flight path. In Figure 8, the required and realized deflection angle of one of the control surfaces are plotted. The required deflection angle is output of the flight control system (FCS) and input to HPAS. The difference between demanded and realized deflection angle as shown in Figure 8 is a measure of the response time of the ISA. Obviously, experimental data are needed to validate the response of the HPAS-model against the real hardware response, and part of the validation process will involve the adjustment of assumed constants in the HPAS-model to get the best agreement with the actual hardware response. Part of the assumptions in the HPAS-model are related to the power losses due to hydraulic pump efficiencies that is converted into heat, for instance which part of the heat is effectively captured in the hydraulic oil and which part is lost to the environment through heat transfer processes. Figure 9 shows the temperature rise due to the hydraulic activity at the ISAs under the current educated assumptions. The relatively high temperature rise at nearly zero time results from the fact that the time-integrated volume is initially very small (close to zero).

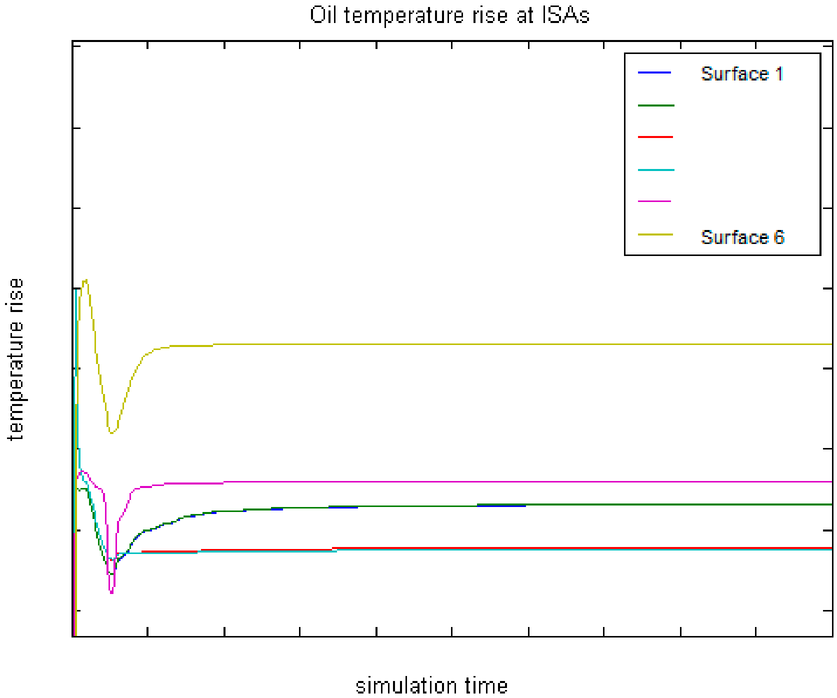

Figure 9. Example of oil temperature rise at ISAs due to control surface deflection.

C. Initial engine model validation

We will start by remarking that there are currently two engine models in the simulation system. The high-level TERTS-based engine model is the one with a central position in the heat and power simulator (see e.g. Figures 2-4) and is driving the shaft power, bleed power, and fuel-oil subsystems. The other engine model is deeply embedded in the AVS-system and serves to deliver flight path data input to the heat and power simulation system in accordance with flight mechanical equations of the moving aircraft. Validation of the high-level engine model can be performed against flight test data, and against data of simulators. Simulators that have generated data for comparison are the engine model of the AVS-system and a full flight simulator at NLR.

To enable validation, a set of flight maneuvers has been selected to be performed in flight tests. These maneuvers have been checked in a full flight simulator before the actual flight tests with an instrumented aircraft took place. Afterwards, the flight tests have been compared to the equivalent maneuvers in the flight simulator to get an impression of reproducibility. An example is depicted in Figure 10, where the time trace of the fuel flow as measured in the flight test is compared with the time trace of the fuel flow in the full flight simulator. Keeping in mind that only the start of the set of maneuvers has been synchronized, this gives an indication of the excellent flying skills of the pilot, keeping in mind that the flight tests and the simulator flights were flown months apart and still show an almost identical fuel flow variation over the duration of the set of maneuvers.

The flight test data are also used to validate the TERTS engine model, amongst others.The TERTS engine model fuel flow is compared to flight test data, using the flight test throttle lever angle as input, see Figure 11. The comparison indicates that the TERTS engine model has adequate fuel flow dynamics indicative for power input into the heat and power management simulation system. A further comparison of thrust and fuel flow data, based on the same throttle lever angle as input, is given in Figure 12. The TERTS engine model fuel flow (second from below in Figure 12) and thrust (upper) are here compared to the AVS fuel flow and thrust values, using the AVS throttle lever angle input (middle). This verification indicates adequate similarity between both engine models.

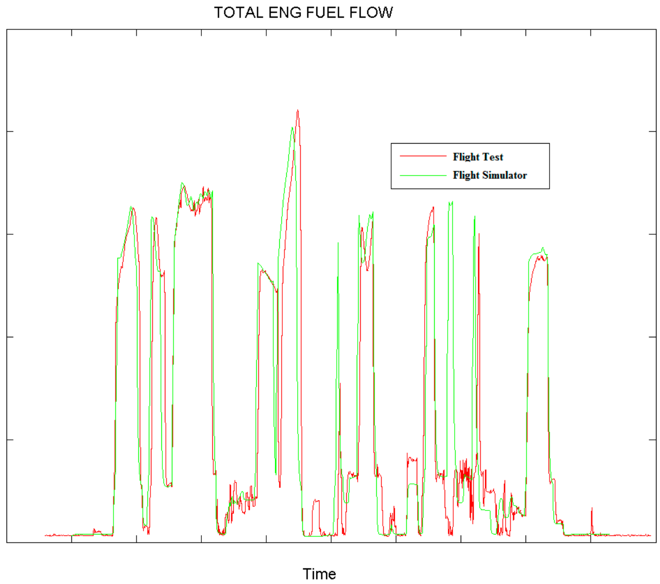

Figure 10. Comparison of fuel flow between flight test and full flight simulator model.

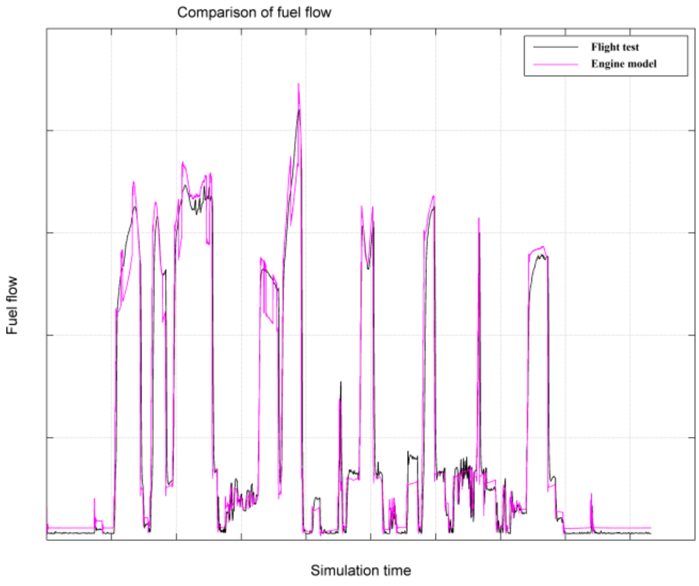

Figure 11. Comparison of fuel flow between flight test and TERTS engine model.

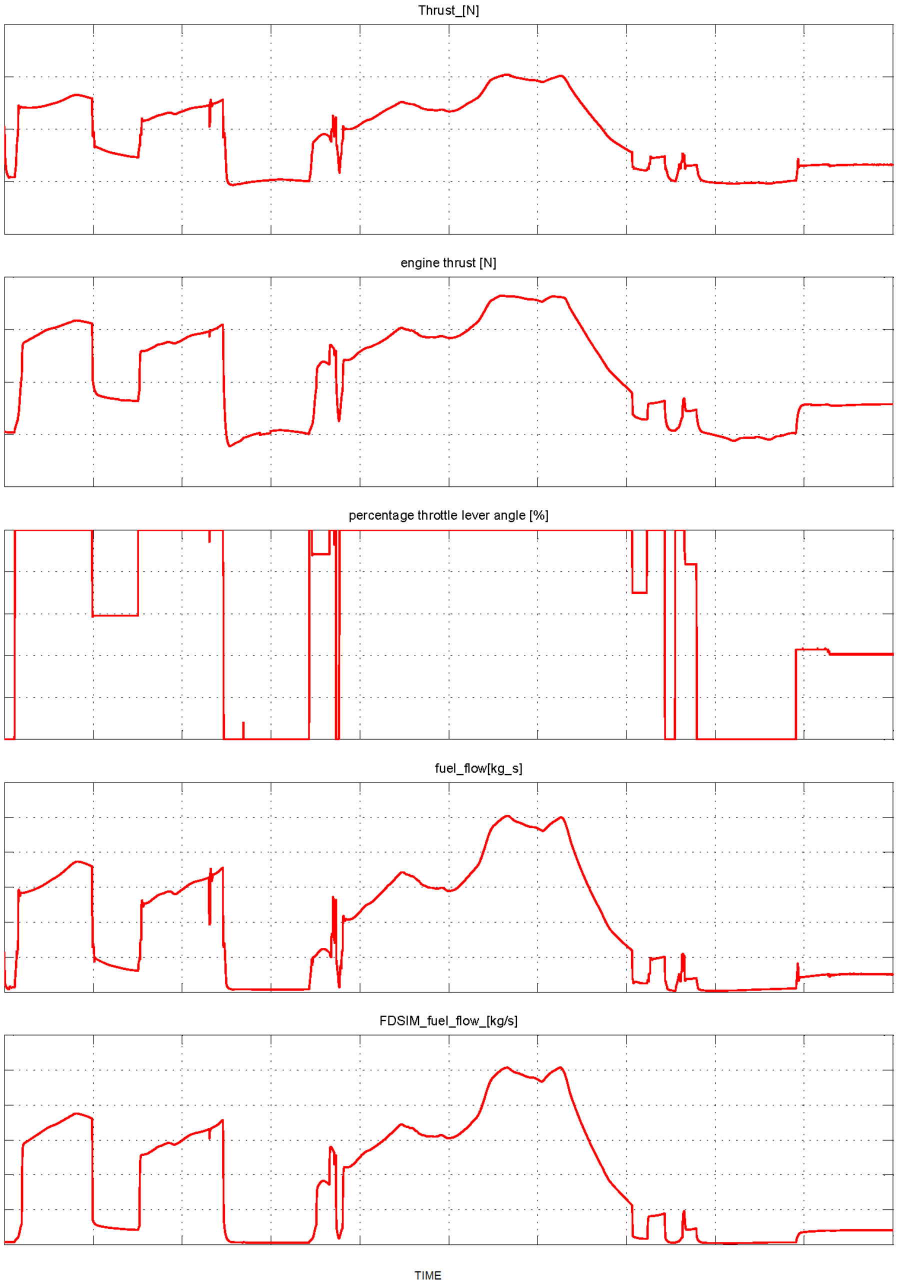

Figure 12. Comparison of thrust and fuel flow between TERTS engine model and AVS-embedded engine model.

VI. Conclusion

A generic approach has been outlined for the development of a heat and power management simulator for aircraft. The simulator aims at achieving an unique level of operational and technical support to aircraft functioning under a variety of conditions, including the capability of identifying critical flight conditions and providing operational optimization within the constraints set by the airframe characteristics. As such, the simulator is initially intended to maintain and assure a valid operational state of legacy aircraft during their remaining life time, although the application to future new aircraft is inherently possible.

The simulator is currently under development; a high-level system architecture has become available identifying the system blocks and their input/output variables. Advanced physics-based models of system components have been developed for the engine, for the hydraulic power actuation system, and for the environmental control system. At a lower level of modeling, a surrogate model of the electrical generator and the electrical power system have evolved, based on experimental data. For the sake of testing and assessing the interaction of models in the high-level architecture, zeroth-order models of components and subsystems are being developed that are based on suitable engineering relations and common sense. Progress on all three levels of modeling is being pursued.

For the verification and validation of the models, a lot of experimental data are required and three levels of testing have been identified as well. We distinguish between component tests, ground tests and flight tests, where the ground and flight tests comprise the interaction of several or all of the aircraft systems. All three levels of testing are deemed necessary for the development of models. Individual component tests are insufficient for a heat and power management simulator verification and validation, although it does provide information that is useful for surrogate model development of the component at hand. Interaction with other systems is however mandatory to asses the full level of operational boundary conditions that a component will undergo in its life time. Ground testing (laboratory test of an airframe with main systems intact and interacting) is intended to provide a first impression of system interaction, serving as guideline for variables to monitor and practical ways to measure data. The experience of component testing and ground testing will feed into instrumented flight tests, defining the focus and viable ways of data acquisition of the most important variables.

Acknowledgments

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