Implementation Approach for an Electrified Aircraft Concept Vehicle in a Research Flight Simulator

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This paper describes a process to develop a flight simulation test capability for the SUbsonic Single Aft eNgine (SUSAN) Electrofan, a subsonic regional jet transport aircraft concept that utilizes electrified propulsion to gain benefits in fuel usage, emissions, and cost. The process, which involves the integration of independently developed models and their subsequent implementation in a flight simulator, is general and can be applied to a variety of aircraft types. However, the use of electrified propulsion architectures has the potential to add complexity beyond that of a traditional aircraft, especially with regard to the pilot interface. The way the pilot interacts with the thrust producing components could vary significantly between architectures, and the information displayed to the pilot will necessarily include additional variables beyond what is normally displayed in a traditional cockpit. This paper describes the integration process in general, as well as specific accommodations made for the architecture under consideration.

I. Nomenclature

AC	=	Alternating Current
AGTF30	=	Advanced Geared Turbofan 30,000 lbf
API	=	Application Programming Interface

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BLI = Boundary Layer Ingesting
DC = Direct Current
DEP = Distributed Electric Propulsion
DRO = Digital Read Out
EAP = Electrified Aircraft Propulsion
EMTAT = Electrical Modeling and Thermal Analysis Toolbox
HEMM = High Efficiency Megawatt Motor
HP = High Pressure
HPC = High Pressure Compressor
HUD = Head Up Display
LP = Low Pressure
LPC = Low Pressure Compressor
MFD = Modular Flight Deck
NPSS = Numerical Propulsion System Simulation
PR = Pressure Ratio
SDK = Software Developer Kit
SM = Stall Margin
SUSAN = SUbsonic Single Aft eNgine (SUSAN)
TCM = Transport Class Model
TEEM = Turbine Electrified Energy Management
T-MATS = Toolbox for the Modeling and Analysis of Thermodynamic Systems
UDP = User Datagram Protocol
VAFN = Variable Area Fan Nozzle

II. Introduction

Electrified aircraft propulsion (EAP) is a major research topic because of the potential benefits it brings in fuel consumption, emissions, cost.[1,2] It is expected to be applied to traditional aircraft[3] and new designs that take advantage of the efficiencies produced by the introduction of electrification. There are also a variety of smaller rotorcraft vehicle concepts that are intended to address the emerging air taxi market.[4] The SUbsonic Single Aft eNgine (SUSAN) Electrofan (Fig. 1) is a subsonic regional jet transport aircraft concept that utilizes EAP to enable propulsive and aerodynamic benefits to reduce fuel usage, emissions, and cost. The target market is the regional low-cost carrier airline with mission specification: 180 passengers; design range of 2500 miles; economic range of 750 miles; and speed of Mach 0.78. The SUSAN concept is representative of the type of aircraft expected to enter service in the 2040 timeframe. The concept is evolving in terms of the number and location of the electric engines, the existence or lack of an empennage, and other features as exploration of the trade space progresses. However, the consistent features include a single boundary layer-ingesting turbofan/generator driving a series/parallel hybrid EAP system (Fig. 2). Generally, a commercial aircraft equipped with a single turbofan engine would present a certification problem, as failure of that engine could prove catastrophic. The SUSAN concept attempts to overcome this by using a battery to provide emergency power to the electric engines. This single use (primary) high specific energy battery is sized for

Fig. 1. Rendering of a recent version of the SUSAN concept aircraft

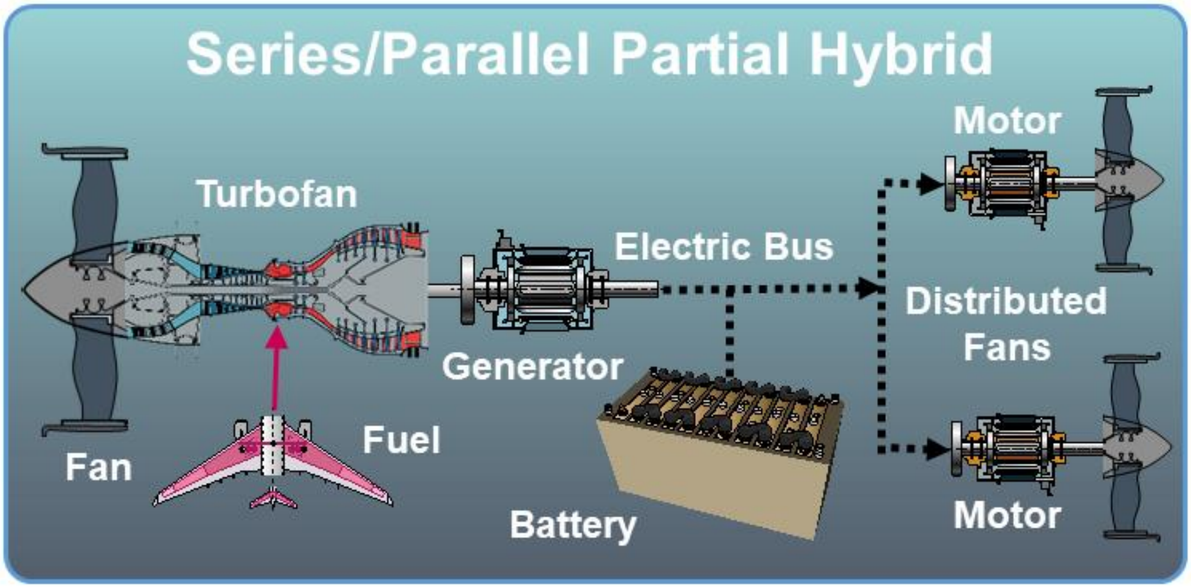

Fig. 2. Series/parallel partial hybrid EAP architecture. The engine produces thrust as well as power for the electric engines.

turbofan engine out fly back and is only used in the case of turbine or generator failure. In addition, a relatively small reusable (secondary) battery is planned for use on all flights to enable EAP benefits. As the SUSAN concept is refined, preparations are underway simultaneously to create the capability to evaluate its performance and handling in a flight simulator. Modular programming approaches and parameterizable modeling tools simplify the initial integration as well as the ability to update the models as necessary. The modeling and integration process is generic, although the details of the EAP architecture are unique and the specific implementation requires customization of the flight deck. The integration process can also uncover gaps and inconsistencies in the in the design.

The rest of this paper is organized as follows. First a description of the software tools will lead into an explanation of the airframe, propulsion, and powertrain systems from a modeling perspective. This is followed by a description of the integration approach used to implement the complete model in the flight simulator. The flight deck design will be the next topic presented. Next, the capabilities and limitations of the resulting model will be discussed, followed by concluding remarks.

III. Software Tools

The turbofan engine will be modeled using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS).[5,6] T-MATS is a NASA-developed library of Simulink® blocks that simplify the dynamic modeling, control design, and analysis of gas turbine engines. Generally, T-MATS models are created at the component level, meaning that each T-MATS block represents a module or other major piece of the engine (inlet, fan, compressor, burner, turbine, nozzle, etc.). The T-MATS model will be generated[7] directly from a 0-D model created using the Numerical Propulsion System Simulation (NPSS®) software,[8] which is used for cycle design. While the NPSS® model is steady state, it provides the necessary data to build a T-MATS model that matches it at the design points. The addition of information such as inertias available from other analysis codes enables the T-MATS model to operate dynamically. It is especially important to note when discussing the modeling of EAP systems that T-MATS can be used to create not only turbine engine models but models of electric propulsive fans as well.[9]

The electrical power system will be modeled using the Electrical Modeling and Thermal Analysis Toolbox (EMTAT).[10,11] EMTAT is a NASA-developed library of Simulink® blocks that simplify the modeling of electrical power systems for EAP applications and is a complementary toolbox to T-MATS. Both T-MATS and EMTAT are highly flexible and parameterizable, so design changes to the turbofan and powertrain made over time can be accommodated easily within the structure of an existing model. Because EMTAT is designed to simulate at the timescale of the shaft dynamics it is a steady state representation of the electrical power system at each time step. Thus, while it does not capture the high-speed electrical transients, it is suitable for modeling the electrical interactions with the turbomachinery. Therefore, the use of T-MATS and EMTAT together facilitates the creation of end-to-end EAP propulsion and powertrain simulations that can execute faster than real time.

X-Plane® is a flight simulation environment for desktop computers. It renders a realistic flight scene while a pilot virtually flies an aircraft. Multiple views from inside or outside the aircraft are available. Flight control is possible through a joystick or a standard mouse. A user can select an aircraft from a built-in fleet containing various aircraft types or can create one using an application called Plane Maker®, which is included (Fig. 3). The user can then fly it using X-Plane®, which calculates flight physics based on blade element theory.[12] Although this technique captures the relevant flight dynamics, the investigational nature and complexity of the SUSAN project demand a more in-depth approach, which shall be described later.

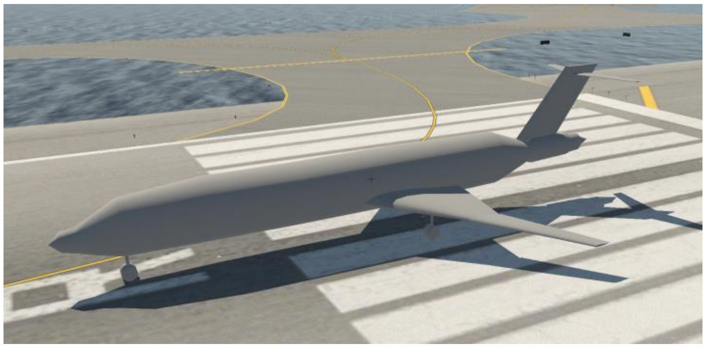

Fig. 3. Basic SUSAN aircraft object created using X-Plane®'s Plane Maker application in the X-Plane® environment.

Software plugins can be utilized to extend the functionality of X-Plane®. Software plugins are specialized application programming interface (API) code that integrates with the X-Plane® software. The ability to create customized aircraft and to employ software plugins makes X-Plane® beneficial for advanced concept research. The flight simulator that will be used for this application is a self-contained modular flight deck (MFD) that offers an immersive and realistic experience with a two-seat cockpit, motion base, and wrap-around out-the-window displays (Fig. 4). It maps the pilot controls into the appropriate inputs to the X-Plane® software. X-Plane® then updates the pilot displays in real time and renders the out-the-window scenery. Pilot and co-pilot instrumentation are designed and created graphically using Plane Maker® and displayed on rectangular screens built into the dashboard visible in Fig. 4.

IV. Airframe Model

A flight dynamics model, preferably created in MATLAB®/Simulink®, is required. Currently, analysis of airframe configurations is underway, but the SUSAN airframe concept has converged sufficiently that a model of the current configuration (as of this writing) should be relatively close to the final version. Placeholders for accepting thrust vectors at specific points on the vehicle are required for integration with the propulsion system. The vehicle should have a flight control, although this is not required for the integration process. However, a flight control is desirable for testing in the flight simulator. If no vehicle model is available, the integration approach can be demonstrated using an existing airframe model, such as the Transport Class Model (TCM).[13]

Fig. 4. Interior view of flight simulation test bed for piloted evaluations.

V. Propulsion and Powertrain Model

The SUSAN propulsion and powertrain design is evolving in terms of the number, type, and location of the electric engines, but the basic concept is fixed: a single boundary layer-ingesting turbofan/generator driving a series/parallel hybrid EAP system with multiple wing-mounted electric engines. The power system contains two types of batteries—a relatively small reusable battery used on all flights to enable EAP benefits, and a single use high specific energy battery only used in case of turbine or generator failure. It also has a four-bus system with opposite rotors connected so that bus failure results in symmetric loads. The battery system is distributed in wing near the electric engines—in wing reduces structural penalty, location near the electric engines reduces cable and makes the system better able to handle failure modes. A diagram of a recent version of the powertrain is shown in Fig. 5. More detail on the power and propulsion systems is given below. The powertrain model is optimized for flight simulation and is a simplified, fast executing representation of more detailed electrical models.

A. Turbofan Engine

The SUSAN turbofan engine (Fig. 6) provides 21,000 lbf of thrust at static sea level and enables extraction of up to 20MW electrical energy, with 30% power extraction at takeoff, and 65% power extraction at altitude. The NPSS version of the SUSAN engine is still under development. Once it is complete, a dynamic T-MATS model will be created as described above. In the meantime, a Simulink® based simplified analytical model that approximates the current iteration of the NPSS data around an operating point, including the power extraction, has been developed. This model is sufficient for powertrain implementation and testing until the T-MATS model is available for use.

The T-MATS model could be created by modifying the existing Advanced Geared Turbofan 30,000 (AGTF30),[14] a publicly available T-MATS model of a generic N+3 (entry-into-service aircraft in the 2030 to 2040 timeframe) engine.[15] Although the design is not final, it is likely that the SUSAN engine will have a similar structure to the AGTF30, but with some major differences. The SUSAN engine is designed to produce about 2/3 as much thrust at

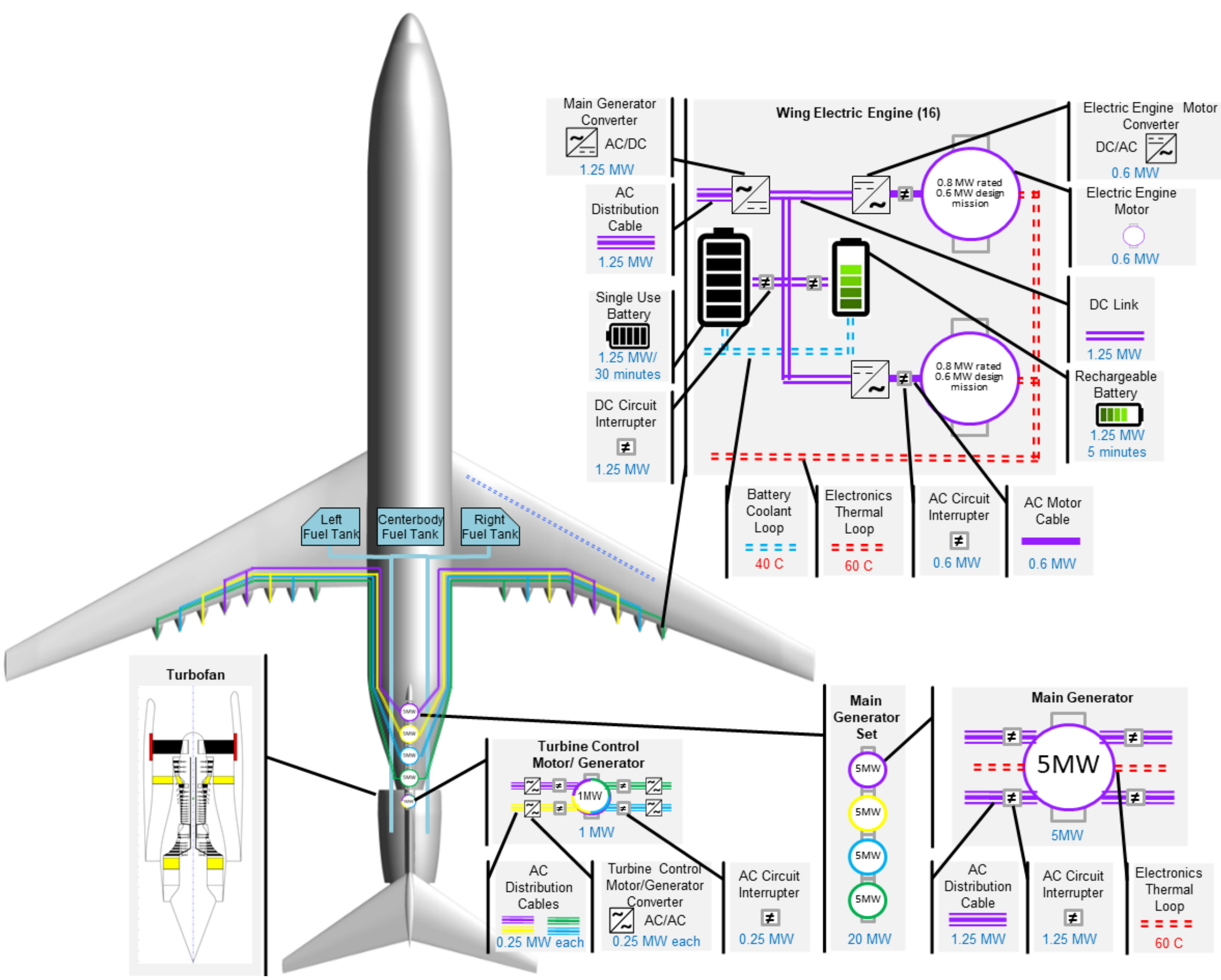

Fig. 5. Diagram of a recent version of the SUSAN powertrain.

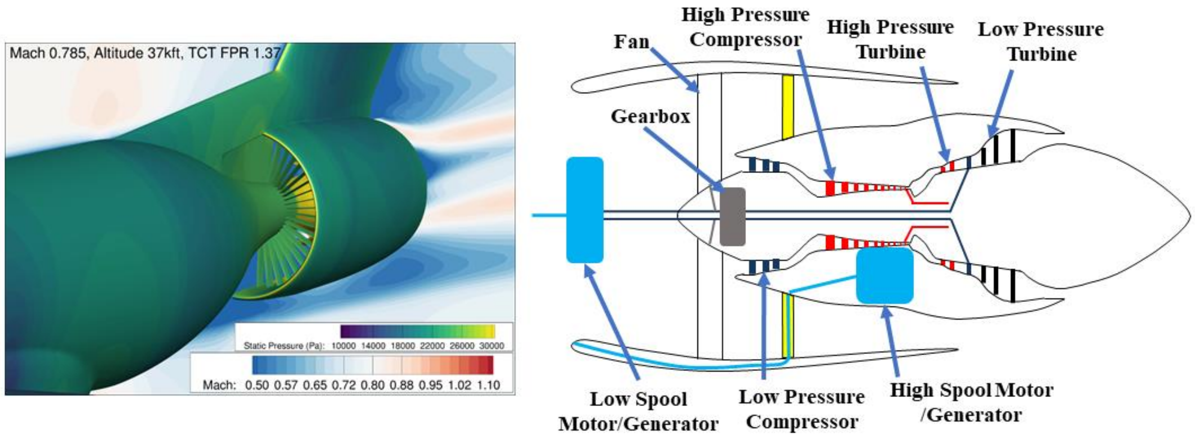

Fig. 6. Boundary layer-ingesting tail turbofan/generator.

sea level and can accommodate a large amount of power extraction. The AGTF30 has a variable area fan nozzle (VAFN) while the SUSAN engine does not. Since T-MATS is parameterizable, the AGTF30 can be resized to match the SUSAN engine's power level, and its VAFN can be set at a fixed opening. The AGTF30 has a full envelope control system, which provides a modifiable structure to use as a starting point for the SUSAN engine's control system.

B. Electric Engines

The electric engines are currently planned to be counter-rotating fans (Fig. 7) in a mail-slot configuration (Fig. 1), eight under each wing. The sixteen propulsors are designed to produce a total of 36,400 lbf of thrust at takeoff (sea level, Mach 0.2) and 7475 lbf at top of climb (37,000 ft, Mach 0.78). For the time being, the performance of each electric engine is modeled using actuator disk theory to calculate the thrust and power generated by these counter-rotating fans, although eventually a higher fidelity dynamic T-MATS models may be created.

C. Power System

The SUSAN power system is structured as a multi-megawatt islanded microgrid, i.e., an isolated microgrid operating in a voltage control mode.[16] As of this writing (Fig. 5), the system consists of 16 alternating current (AC) electrical buses, four of which are connected to each of four main generators on the turbofan low pressure shaft. Each of the buses has its own 3-phase AC electrical cable out to the wing electric engine area, where it supplies a single electric engine. Furthermore, each of the 16 electric engines has an AC/DC converter, two batteries, two DC/AC converters, and two motors.

The 3-phase AC power arrives from the generator and is converted to DC power, where it is connected to two batteries. One battery is a single-use primary battery for emergencies only; it is connected when the feed from the main generator is unpowered due to a generator or turbofan engine failure. The primary battery provides emergency

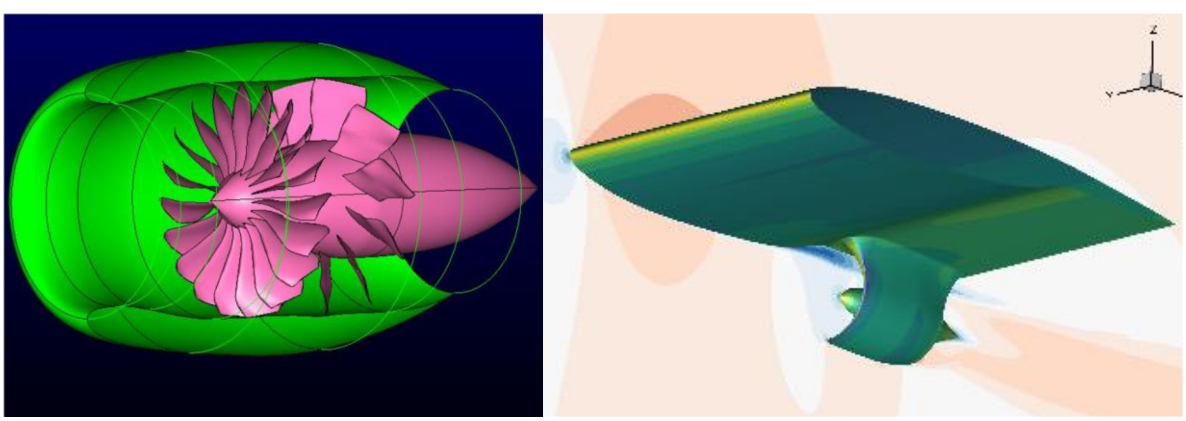

Fig. 7. Counter-rotating electric fan (left) mounted underwing (right). The current plan calls for eight such electric engines per side.

power for a 300-mile range (30 minutes at Mach 0.8), which is sufficient to reach a primary airport from most of the continental United States. The rechargeable secondary battery is used to smooth out fluctuations in generated electrical power and to provide a power boost when necessary. Each DC/AC converter serves as the motor controller for one of the two motors in the electric engine. Each motor provides power to one of the two counter-rotating fans on the electric engine. There is also a turbine control motor/generator attached to the engine's high-pressure shaft, which is used to improve dynamic operation of the engine during transients.

The power system is modeled using EMTAT. Each component in the powertrain is modeled with a matching component in EMTAT. There are multiple instances of several of the subsystems in this model, so they are being created as their own Simulink® models; then these model files are referenced in the larger model.

D. Control

The SUSAN turbofan incorporates the Turbine Electrified Energy Management (TEEM)[17,18] control, implemented through the powertrain system. The TEEM concept uses electric machines (motor/generators) attached to the high- and low-pressure shafts of the engine (Fig. 5) as additional actuators incorporated into the control system. During transient operation, the electric machines add power to or extract power from the shafts as appropriate to coordinate the acceleration and deceleration of the spools. This maintains operation near the operating line rather than allowing the transient off-design excursion typical of turbine engines with traditional control systems (Fig. 8). This approach can significantly reduce the required transient allowance set-aside[19] normally designed into the compressor and potentially result in performance and efficiency benefits.[17] TEEM has already been successfully demonstrated on the AGTF30 model with a modified control system.[18] This provides an example upon which to base the required modification for the SUSAN engine implementation.

E. Dynamic Powertrain Model

The parts of the overall dynamic powertrain model described above are created using the Simulink® based tools, T-MATS and EMTAT. Because the systems and subsystems are all modular with defined interfaces, the model can be updated in a relatively straightforward way. This enables developers to keep the powertrain model current as the SUSAN design evolves.

An initial dynamic simulation of the powertrain is under development. The time response of an analytical model of the turbofan engine configured with a preliminary control system is shown in Fig. 9. The analytical model is

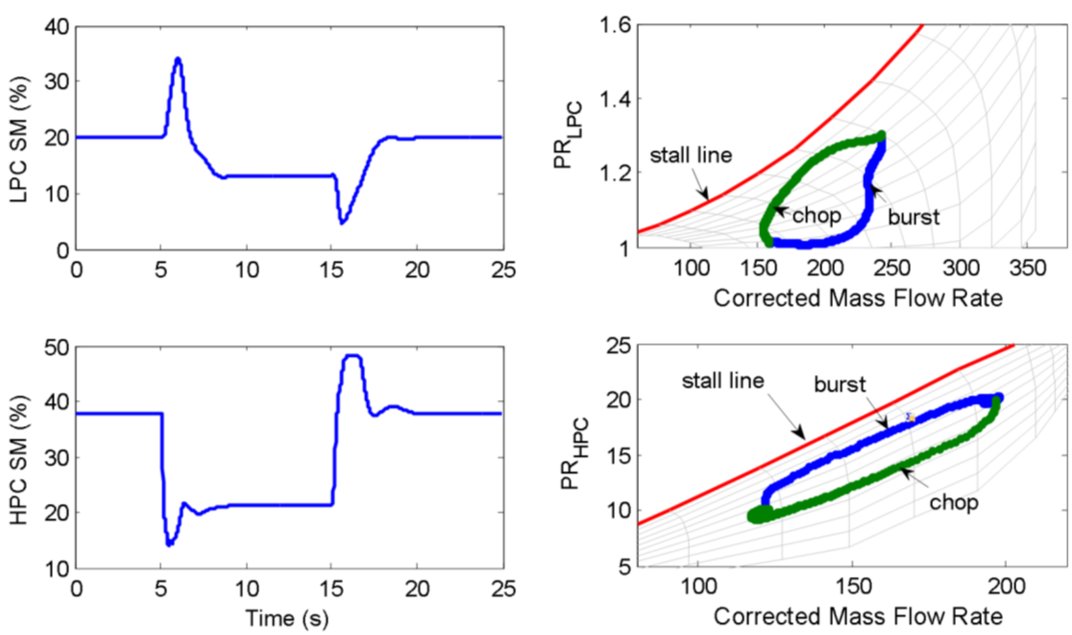

Fig. 8. Example burst/chop surge margin (SM) trajectories vs. time for a turbofan engine with a traditional control system (left), shown in relation to the LPC and HPC pressure ratio (PR) vs. corrected mass flow rate maps (right). The compressor operating line (not shown) is a relatively straight line that connects the beginning and end of the transient on each of the compressor maps.

responding to changes in low-pressure (LP) shaft speed command, followed by changes in the power extraction demand, first from the LP shaft, then from the high-pressure (HP) shaft. The power extraction demand is shown as a net torque change, along with the corresponding power made available to the rest of the powertrain. The net torque is the total torque minus that required to turn the spools and gearbox. The analytical engine model exhibits the expected behavior and has the appropriate interface to be integrated with an EMTAT power system model. Thus, it could be part of a complete propulsion and powertrain model, and it can be replaced by a T-MATS model when available.

VI. Integration

There are two types of integration involved with this effort: integration of the airframe model with the propulsion and powertrain model, and integration of this aforementioned aircraft simulation ("aircraft model") with X-Plane®.

A. Integration of the Airframe Model with the Propulsion and Powertrain Model

The SUSAN airframe flight dynamics model and the propulsion and powertrain model are created separately. The earliest version of the airframe model, whether specifically the SUSAN vehicle or the stand-in TCM, will have a simplified interface with the propulsion and powertrain model. The variables passed in this case are: Mach number, altitude, ambient temperature and pressure, and throttle position from the airframe to the propulsion system, and thrust

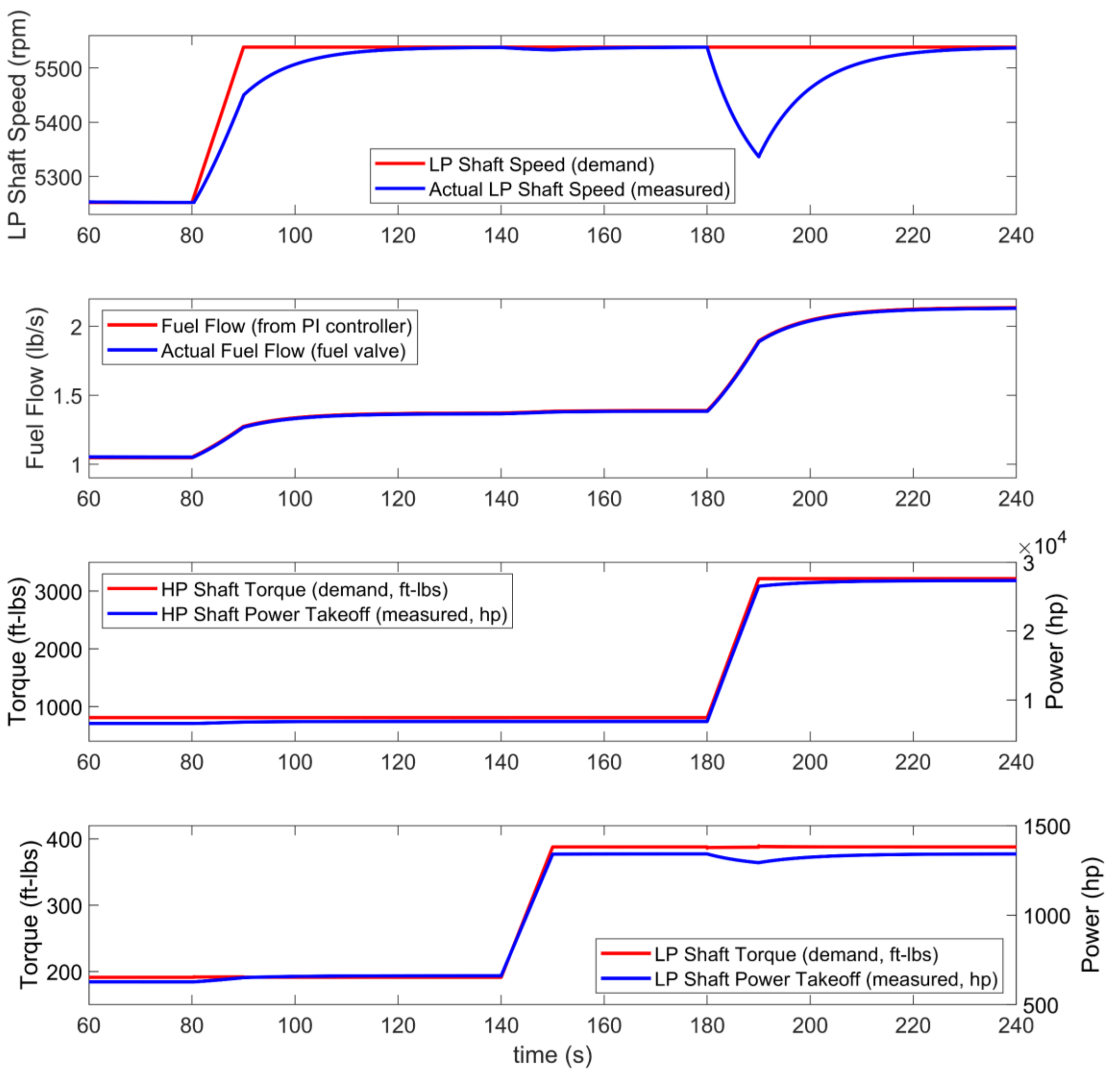

Fig. 9. Dynamic simulation of the turbofan engine with hooks to the rest of the SUSAN powertrain. Changes in the speed command followed by changes in torque demand (power extraction) on the LP shaft then the HP shaft and resulting changes in variables are shown.

and potentially fuel flow from the propulsion system to the airframe.[20] The propulsion system thrust, which is a function of aircraft conditions, will act on the airframe through force vectors applied at the appropriate locations. The integration of these two models is straightforward, as long as the interface is clearly defined and the update rate of each is properly accounted for. This type of integrated model is a starting point but does not account for the aero-propulsive interactions that will provide some of the anticipated efficiency benefits of the SUSAN concept.

The current SUSAN design incorporates both a Boundary-Layer-Ingesting (BLI) turbofan engine in the aircraft's empennage and a distributed electric propulsion (DEP) system consisting of 16 counter-rotating fans with BLI under the wings, in a mail-slot configuration. The benefit of BLI comes from accelerating low velocity air (the air in the boundary layer) as opposed to freestream air.[21] The advantages of DEP are configuration-dependent, but include increased lift, delayed turbulent separation, and reduced drag.[22] An aircraft model that incorporates these aero-propulsive interactions is more complex than the assumed non-interacting aircraft model implementation described above.[23] However, modifications to include the interactions should only consist of extensions to this aircraft model, requiring possibly an expanded interface between the aircraft, propulsion, and powertrain models.

Finally, the integrated model must run faster than real time to allow for real-time implementation in a flight simulator. The model is formulated such that it steps through time at a fixed update rate. It executes one simulation time step, then waits until the start of the next clock time interval to execute the next simulation step. As long as a simulation step can complete before the end of the clock time interval it represents, the simulation can be slowed down to run in real time using a Simulink® RealTime Pacer block. For previous integrated model implementations, the one described in Ref. 20 for example, this type of soft real-time execution has been achieved without requiring the use of the acceleration mode in Simulink® or other compilation techniques. For reference, the time step for the aircraft model described in Ref. 20 (both engine and airframe) is 0.015 sec. The data transfer rate between the simulation running on an external computer and the flight simulator computer can be much faster (200 Hz) to accommodate models with higher update rates, but data transfer should occur at least once per model update interval. This is all independent of the 60 Hz refresh rate X-Plane® uses for the flight simulator's graphics, but if the model updates too slowly, the animation will not appear smooth to the viewer.

B. Integration of the Aircraft Model with X-Plane® in the Flight Simulator

As mentioned previously, X-Plane® simulates flight dynamics internally using blade element theory[12] on an aircraft object Fig. 3). The aircraft model used here is written in an arbitrary language (although Simulink® is most often used), and it runs on an external computer, not one that is part of the MFD. X-Plane® continues to generate internal flight dynamics regardless of the presence of an external model. Some of the internal X-Plane® flight dynamics models have been integrated with the MFD cockpit in such a way that the pilot control inputs map into the appropriate data locations in the X-Plane® flight dynamics model, and the aircraft variables are presented appropriately on the built-in cockpit displays. By selecting an internal X-Plane® flight dynamics model that represents an aircraft with a similar configuration to the one represented by the external model, the existing interfaces between the MFD and X-Plane® can be leveraged to tie the external aircraft model to the cockpit. Utilizing this framework, variables passed between X-Plane® and the external aircraft model are mapped into the cockpit such that the pilot controls and displays tie directly into the external simulation, overwriting the variables calculated internally by X-Plane® at each time step. This enables the pilot to fly the external model from the MFD cockpit. Furthermore, additional data connections can be defined, providing for more variables (e.g., electrical variables for cockpit displays) to be passed.

The flight simulator contains the MFD and two desktop computers that allow external aircraft models to be incorporated. Communication between the MFD and the desktop computers is facilitated by a network connection. Communication between the aircraft model and X-Plane® is accomplished using the User Datagram Protocol (UDP). UDP is a simple protocol with low latency that is ideal for real-time applications. Data are transmitted without acknowledgment of reception. Without acknowledgment, there is no guarantee of data packet delivery, order of reception or protection from data packet duplication. Therefore, UDP is ideal for time sensitive applications where data loss is preferred over time delays resulting from the need to resend data packets.

To enable X-Plane® network communication, a software plugin is employed. Software plugins enable programmers to write code to add special or unique features to X-Plane®. The code must follow a particular template and utilize the plugin Software Developer Kit (SDK) for X-Plane® compatibility. In this application, a software plugin will be used to send pilot commands to the aircraft model and receive aircraft status and position information for the instrument panel and to render the flight scene. When the information is received, the plugin overwrites the X-Plane®

internal model output with the new input. Because the plugin operates at 200 Hz (0.005 seconds), the internal X-Plane® and aircraft models are synchronized enough for no visual disturbances to be observed.

VII. Flight Deck Design

The pilot interface is an important feature in cockpit design, and new concepts related to EAP will require new displays including relevant power system data, e.g., battery state of charge. Furthermore, the concept of operations related to thrust generation needs to be defined. Such considerations as how much thrust is produced by the turbofan engine and how much by the electric engines, how much of the electricity is produced by the batteries and how much by power takeoff from the turbofan engine, etc., must be coordinated and optimized as a function of flight condition. Appropriate displays and control knobs must be designed. Private industry as well as NASA are starting to develop all-electric vehicles, but there is little precedent for cockpit displays in vehicles with turboelectric propulsion. The cockpit display of NASA's all-electric X-57 Maxwell contains multiple screens that include health and status information from the battery management system, cruise motor controller, and throttle encoders while also showing warnings and alarms based on data from these systems.[24] Conceptually, the SUSAN display should represent a futuristic aircraft for the 2040 timeframe. The type of information displayed will depend on the pilot's ability to act on it, which in turn relates to the level of automation.

The initial attempt described below owes much to standard cockpit displays, augmented with corresponding information related to the power system. The flight simulator implementation is limited by the capabilities of customization in the MFD and X-Plane®. The inclusion of a Head-Up Display (HUD), implemented either on a separate see-through dashboard-mounted display or directly superimposed on the out-the-window scenery, and a multi-page touchscreen, perhaps implemented on a tablet, will give a hint of a futuristic, information rich cockpit. The throttle quadrant will probably be limited to four or fewer throttles, and certain other details will probably be ignored for now to further simplify the implementation. These relate to as yet unanswered questions about, for instance, the existence and/or operation of thrust reversers.

An early SUSAN display concept is shown in Fig. 10. The display concept is designed to be fairly complete yet fit into the relatively small instrumentation screen in the dashboard. The designers' objective was to compartmentalize information while keeping the overall layout simple. This compartmentalization serves to organize the display and

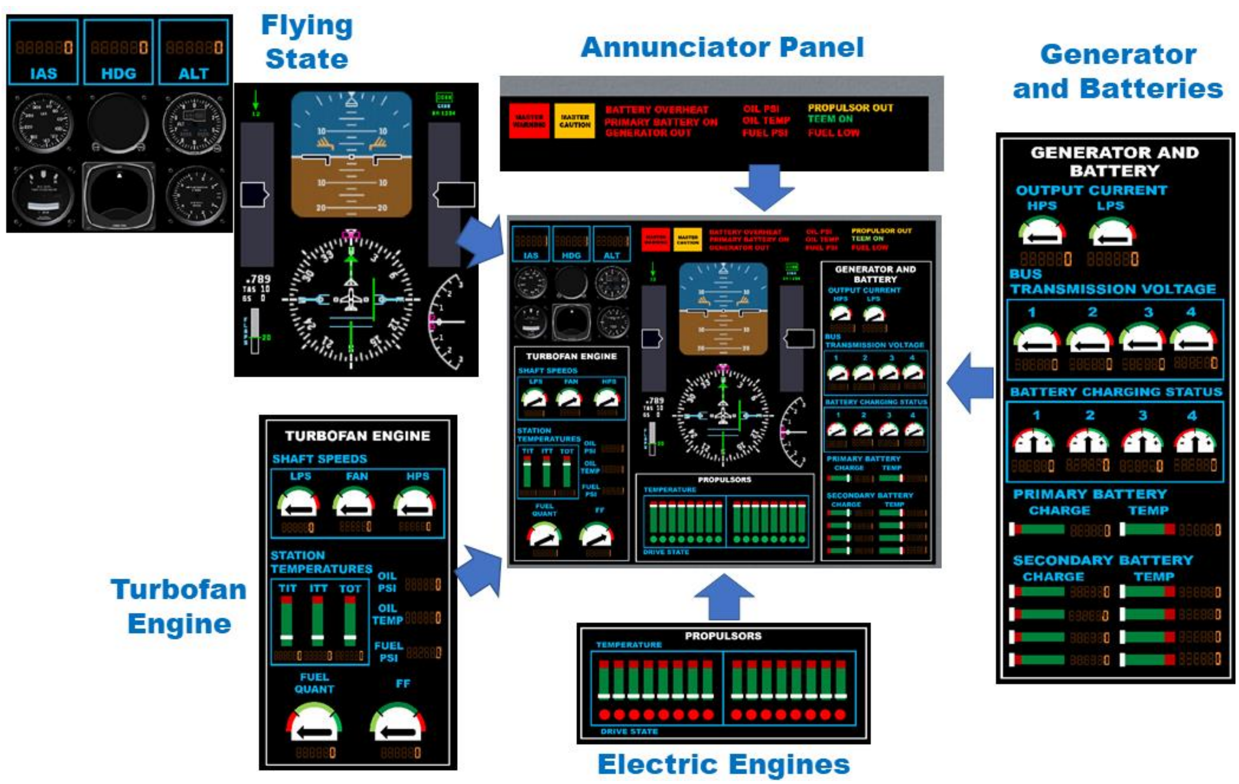

Fig. 10. Exploded view of an early SUSAN pilot display. The central section shows the pilot display as implemented with the surrounding sections comprising the individual components.

facilitates a clear understanding of the information presented. Displays and fonts follow readability standards.[25] In future iterations the pilot and copilot side of the cockpit will most likely differ in information. Flight status, position, and urgent messages should populate the pilot side; diagnostics and subsystem details should be placed on the copilot side. Splitting up indicators between both sides of the cockpit will decongest the displays.

A. Flying State of the Aircraft

This section of the display (upper left of Fig. 10) contains the six standard flight indicators: airspeed indicator, altimeter, turn coordinator, artificial horizon, vertical speed indicator, and heading. This display provides the pilot with the most important information needed to fly, and therefore it is prominently featured in the center of the display.

B. Generator and Battery

This section of the display is at the right side of Fig. 10. On the top of the panel, there are Digital Read Outs (DROs) and dials showing the output current for the low-pressure and high-pressure shaft generators. The generator attached to the low-pressure shaft transmits power through the four AC buses. Transmission voltage is displayed on both a DRO and dial for each bus. The power from the LP shaft is distributed through the buses to each battery. The pilot can see the battery charging status, i.e., the net current into the battery. When the battery is discharging toward the electric engines, it has a negative charging status. The green area of the dial is positive, and the red is negative. The four dials that display battery charging status differ from the charge status indicators. Charging status is measured in amperes, while charge status is measured in volts. Charge status and temperature measurements are displayed on both horizontal tapes and DROs at the bottom of this section for both the primary and secondary batteries.

C. Electric Engines

The display contains a section devoted to the 16 wing-mounted electric engines (bottom center of Fig. 10). The drive state for each electric engine is displayed via a circular light: red when the electric engine is not running and green when it is “energized” and producing thrust. This binary light is the most efficient way to show the pilot which electric engines are working and which, if any, are malfunctioning. Electric engine health is represented by temperature and drive state. This design assumes an electric motor similar to the High Efficiency Megawatt Motor (HEMM), and the temperature is measured from within the electric motor coils.[26] Current is a similar measurement, and so both are not shown. If the electric engine starts requiring a large amount of current, the temperature will rise, and may indicate an electric engine malfunction. The top of the temperature bar is red to illustrate the over temperature range. The temperature ranges will need to be incorporated into these indicators once the motors are fully characterized.

D. Turbofan Engine

This display contains much of the turbofan-related information commonly seen in today’s aircraft (bottom left of Fig. 10). At the top of this section, there are three dials that display the HP, LP, and fan shaft speeds. The low-pressure and fan shaft are connected by a gear box, so they are right next to each other. Below these, three turbine station temperatures are displayed with vertical tapes. Alongside these are three DROs for the oil pressure, fuel pressure, and the oil temperature. Corresponding warnings for these can be found on the annunciator panel. These indicators are based on observations of standard engine readouts from common aircraft cockpits. Dials displaying fuel flow rate and fuel quantity are also present.

E. Annunciator Panel

An annunciator panel (top center of Fig. 10) displays alert lights. As in most commercial aircraft, the SUSAN design contains a master caution and master warning light that illuminate when an event occurs, and another alert light with a description of the event. The purpose of the lights is to bring attention to the annunciator panel. Annunciators are hidden when they are not engaged, which reduces confusion and keeps the display clean. As in today’s aircraft, most malfunctions will be handled internally via control protocols, so the pilot would not need to be alerted.[27] The only events that will need to be communicated to the pilot are those that require pilot action. All annunciated messages should be cancelled after a certain amount of time.[25]

With each of these pieces, the pilot should have a full picture of the powertrain status and health.

VIII. Discussion

Electrification is bringing about major changes in aircraft that will necessarily be reflected in the flight deck. The power system will become integral to propulsion and therefore safety, so information related to its condition will need to be displayed. Further, in traditional aircraft when not utilizing a highly automated flight control mode, the pilot is the integrator, flying the plane and commanding engines independently, each with its own thrust lever. Most of today's commercial aircraft have two engines, so moving the throttles individually is intuitively meaningful. Even the B-52's eight throttles can be moved together with one hand,[28] and individually as necessary, so the workload is manageable. In the current SUSAN configuration with a turbofan engine and 16 electric engines, the pilot would need to either move an incredible 17 thrust levers at once, or a smaller number where some command multiple electric engines; flight simulator studies with pilots could help determine the most reasonable approach. A complicating factor is that in SUSAN, the electric engines are not independent of the turbofan engine, they are powered by it, so it would not be feasible under normal circumstances to idle the turbofan engine and still fly without using the primary battery, which is reserved for engine out or generator failure situations. A final point is that to achieve the benefits of EAP and DEP, the flight control will certainly be highly automated and may even utilize differential thrust for maneuvering.[29] For these reasons it is hard to envision the pilot moving the thrust levers individually except under specific emergency scenarios.

Within the flight simulator itself, the ability to update the flight deck to represent that of a 2040 entry-into-service vehicle with electrified propulsion is limited because of the infrastructure of the existing cockpit. Still, efforts to understand and define the requirements of a 2040 flight deck are underway, and as the vision takes shape, a path to subsequently translate it into something that can be approximated in the existing cockpit is being considered.

Evolution of the SUSAN airframe configuration continues as trade studies investigate a variety of features in an attempt to optimize metrics in a realistically achievable way. The flight control approach is an area that must be addressed because it ties together the vehicle, power, and propulsion in a way that enables optimal system-level performance, taking advantage of the individual enhancements offered by component level optimization. The integrated aircraft model being developed for the flight simulator implementation will provide a suitable testbed on which to evaluate optimal control and coordination schemes, much the way the benefits of the TEEM control were demonstrated in simulation.[17,18] Because the SUSAN aircraft model will be standalone and execute faster than real time, it will be ideal for performing desktop simulations to test control methodologies within the MATLAB® environment, which enables immediate analysis of the resulting data. In this way, for instance, incorporation of DEP into the flight control can be tested, evaluated, and optimized.

IX. Concluding Remarks

This paper describes the on-going implementation of a SUSAN aircraft model in a flight simulator. It describes the various disparate parts and how they are to be integrated. Because the final design is not set, the pieces are being developed in a modular way so changes can be incorporated without starting from scratch; the use of NASA-developed Simulink® based modeling tools for the turbomachinery and power system helps facilitate this modular approach. Initial airframe and powertrain models will start relatively simple with the opportunity to increase fidelity over time by, for instance, capturing the aero-propulsive interactions between the airframe and the thrust producing components. The model development and integration can expose design inconsistencies, especially when pieces of the system are being developed and optimized individually, and the integrated model can be used to perform trade studies beyond what can be achieved with the individual pieces alone. Finally, an effort to define the flight deck requirements for a highly optimized propulsion integrated aircraft with EAP is underway. The effort includes requirements for pilot displays and pilot controls. Aspects of this effort will be incorporated into the flight simulator where possible, but the overall concept will provide direction for future flight deck implementations.

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References

[1] Jansen, R. H., Bowman, C. L., Jankovsky, A., Dyson, R., and Felder, J., "Overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transport," AIAA Paper 2017-4701, July 2017.

[2] Bowman, C. L., Felder, J. L., and Marien, T. V., “Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport,” AIAA Paper 2018-4984, July 2018.
[3] Welstead, J., and Felder, J., “Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion,” AIAA Paper 2016-1027, January 2016.
[4] Johnson, W., Silva, C., and Solis, E., “Concept Vehicles for VTOL Air Taxi Operations,” AHS International Technical Meeting Aeromechanics Design for Transformative Vehicle Flight. San Francisco, CA, 16–19 January 2018.
[5] Chapman, J. W., Lavelle, T. M., May, R. D., Litt, J. S., and Guo, T.-H., “Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User’s Guide,” NASA/TM—2014-216638, January 2014.
[6] Chapman, J. W., Lavelle, T. M., May, R. D., Litt, J. S., and Guo, T.-H., “Propulsion System Simulation Using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS),” AIAA Paper 2014-3929, July 2014.
[7] Chapman, J. W., Lavelle, T. M., Litt, J. S., and Guo, T.-H., “A Process for the Creation of T-MATS Propulsion System Models from NPSS Data,” AIAA Paper 2014-3931, July 2014.
[8] Jones, S.M., “Steady-State Modeling of Gas Turbine Engines Using the Numerical Propulsion System Simulation Code,” GT2010-22350, *ASME Turbo Expo 2010: Power for Land, Sea, and Air*, Glasgow, UK, 14–18 June 2010.
[9] Connolly, J.W., Chapman, J.W., Stalcup, E.J., Chicatelli A., and Hunker, K.R., “Modeling and Control Design for a Turboelectric Single Aisle Aircraft Propulsion System,” AIAA Paper 2018-5010, July 2018.
[10] Bell, M. E., and Litt, J. S., “Electrical Modeling and Thermal Analysis Toolbox (EMTAT) User’s Guide,” NASA/TM-20205008125, October 2020.
[11] Bell, M. E., and Litt, J. S., “An Electrical Modeling and Thermal Analysis Toolbox for Electrified Aircraft Propulsion Simulation,” AIAA Paper 2020-3676, August 2020.
[12] “How X-Plane Works,” *X-Plane 11*, Accessed 12 August 2021. https://www.x-plane.com/desktop/how-x-plane-works/ [retieved 12 August 2021].
[13] Hueschen, R. M., “Development of the Transport Class Model (TCM) Aircraft Simulation from a Sub-Scale Generic Transport Model (GTM) Simulation,” NASA/TM–2011-217169, August 2011.
[14] Chapman, J. W., and Litt, J. S., “Control Design for an Advanced Geared Turbofan Engine,” AIAA Paper 2017-4820, June 2017.
[15] Jones, S.M., Haller, W.J., and Tong, M.T., “An N+3 Technology Level Reference Propulsion System,” NASA/TM—2017-219501, May 2017.
[16] Jain, M., Gupta, G., Masand, D., Agnihotri, G., and Jain, S., “Real-Time Implementation of Islanded Microgrid for Remote Areas,” *Journal of Control Science and Engineering*, Vol. 2016, Article ID 5710950, 2016.
[17] Culley, D., Kratz, J., and Thomas, G., “Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs,” AIAA Paper 2018-4798, July 2018.
[18] Kratz, J. L. Culley, D. E., and Thomas, G. L., “A Control Strategy for Turbine Electrified Energy Management,” AIAA Paper 2019–4499, August 2019.
[19] Walsh, P. P., and Fletcher, P., Gas Turbine Performance, Blackwell Science/ASME, 2004.
[20] Litt, J. S., Sowers, T. S., Liu, Y., Owen, A. K., and Guo, T.-H., “Validation of an Integrated Airframe and Turbofan Engine Simulation for Evaluation of Propulsion Control Modes,” AIAA Paper 2015-1476, January 2015.
[21] Lee, B.J., Liou, M.-F., Celestina, M., and To, W., “Benefit and Critical Factors For The Performance of the Boundary Layer Ingesting Propulsion,” GT2020-15596, *Proceedings of the ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition*, 21-25 September 2020.
[22] Erhard, R. M., Clarke, M. A., and Alonso J. J., “A Low-Cost Aero-Propulsive Analysis of Distributed Electric Propulsion Aircraft,” AIAA Paper 2021-1200, January 2021.
[23] Gray, J. S., Mader, C. A., Kenway, G. K. W., and Martins, J. R.R.A, “Modeling Boundary Layer Ingestion Using a Couple Aeropropulsive Analysis,” *Journal of Aircraft,* Vol. 55, No. 3, May-June 2018.
[24] Clarke, S., Redifer, M., Papathakis, K., Samuel, A., and Foster, T., “X-57 Power and Command System Design,” *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, Chicago, Illinois, 22-24 June 2017.
[25] Yeh, M., Swider, C., Jin Jo, Y., and Donovan, C., “Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls,” US Department of Transportation, Version 2.0, 2016.
[26] Jansen, R. et al., “High Efficiency Megawatt Motor Preliminary Design,” AIAA Paper 2019-4513, August 2019.
[27] Advisory Circular 25.1322-1: Flightcrew Alerting. US Dept. of Transportation, Federal Aviation Administration, 13 December 2010.
[28] Consoli, F., “Tales From The Cockpit: Testing The B-52 Stratofortress Bomber With The USAFTPS At Edwards AFB,” URL: https://theaviationist.com/2021/02/07/tales-from-the-cockpit-testing-the-b-52-stratofortress-bomber-with-the-usaftps-at-edwards-afb/ [retrieved 20 October 2021].
[29] Nguyen Van, E., Troillard, P., Jézégou, J., Alazard, D., Pastor, P., et al., “Reduction of Vertical Tail Using Differential Thrust: Influence on Flight Control and Certification,” *Advanced Aircraft Efficiency in a Global Air Transport System (AEGATS’18)*, October 2018, Toulouse, France.