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Preliminary Dynamic Modeling of a Quarter-Scale Distributed Electric Propulsion Aircraft

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Abstract

This paper describes the early-stage modeling of a quarter-scale distributed electric propulsion aircraft, based on the SUbsonic Single Aft eNgine (SUSAN) Electrofan, a transformative concept aircraft for which a model exists. The full-scale 180 passenger SUSAN concept has a single turbofan engine in the tail that both produces thrust and provides electrical power to 16 electric fans distributed across the wings utilizing a series/parallel hybrid architecture. The quarter-scale version would have an internal combustion piston engine to provide power to 17 electric fans—16 on the wings, one in the tail—in a series hybrid configuration, and no vertical or horizontal stabilizers. It would also have a reduced flight envelope in terms of both altitude and speed. The initial modeling approach is to scale down the original airframe model to capture the dynamic behavior of a much smaller aircraft, albeit with an empennage.

The original powertrain model is then replaced with one representing the physical components of that of the quarter-scale vehicle. This powertrain model is suitable for control design and analysis, and the fully integrated, although preliminary, aircraft model allows flight simulator testing and evaluation. Results from simulations are presented.

1.0 Introduction

Electrified aircraft propulsion (EAP) is a major research topic. It is expected to be applied to traditional looking aircraft, and new designs that take advantage of the efficiencies produced by propulsion-airframe integration and the introduction of electrification. There are also a variety of smaller rotorcraft vehicle concepts that are intended to address the emerging air taxi market. The SUbsonic Single Aft eNgine (SUSAN) Electrofan (Figure 1) is a subsonic regional jet transport aircraft concept that utilizes EAP to enable propulsive and aerodynamic benefits to reduce fuel usage and cost (Refs. 1 and 2) and improve safety, reliability and efficiency across the flight envelope. It is representative of the type of aircraft that could enter into service in the 2040 timeframe and assumes that the future enabling technology will be available. It has a single thrust producing, boundary layer-ingesting (BLI) geared turbofan (GTF) engine with generators driving a series/parallel partial hybrid EAP system. The architecture includes 16 underwing contrarotating BLI fans, or wingfans, eight on each side, in a mailslot configuration. The 16 fans run on power extracted from the GTF through four 5 MW generators connected to the low-pressure spool (LPS), and a single 1 MW generator on the high-pressure spool (HPS). The wingfans generally provide about 65% of the thrust across the flight envelope while the GTF provides the remainder. The SUSAN concept includes single-use batteries for emergency wingfan power in case of GTF or generator failure.

Figure 1. Rendering of the SUSAN concept aircraft.

In the near-term, design of a quarter-scale flight vehicle, based on the full-scale SUSAN concept, that could eventually be built, was begun (Figure 2). This hybrid electric unmanned aerial vehicle would be in the size class of a general aviation aircraft. It would be a research platform to allow rapid, low cost, high risk, iterative technology, component, system, and vehicle research and integration developments. This vehicle design specifies that it is to have no empennage. To make up for the lack of a rudder for maneuvering, the wingfans could have thrust vectoring nozzles. The powertrain of this smaller vehicle would include a reciprocating engine to provide power to 17 fans, 16 underwing, similar to the full-scale SUSAN powertrain, and one in the rear where the full-scale version's GTF resides. The powertrain design includes batteries to source and sink power, and for stabilization of the electrical bus. Because the reciprocating engine produces no thrust, the quarter-scale vehicle's powertrain has a series hybrid architecture (Figure 3).

The rest of this paper is organized as follows. First is a discussion of the airframe model, followed by the powertrain design, consisting of the engine, power system, and propulsors, and then, the thermal management system. Next, a description of the software tools will lead into an explanation of the integration approach. The pilot interface will be the next topic presented. Finally, the capabilities and limitations of the resulting model will be demonstrated and discussed, followed by conclusions.

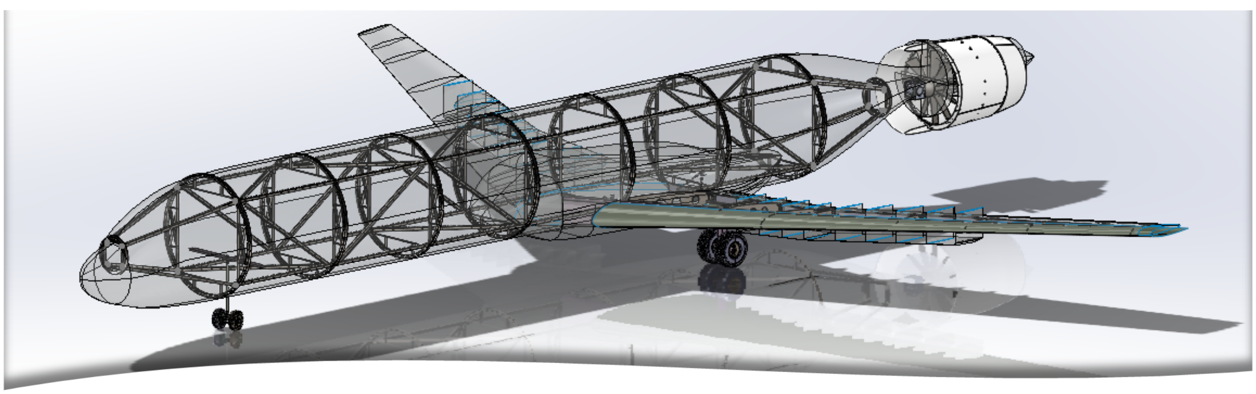

Figure 2. Frame of the quarter-scale distributed electric propulsion aircraft.

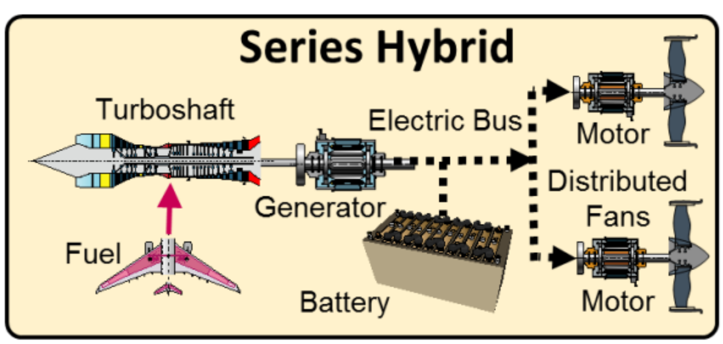

Figure 3. Generic series hybrid EAP architecture. The quarter-scale SUSAN vehicle will have a piston engine rather than a turboshaft engine.

Table 1. Flight Envelope of Quarter-Scale Distributed Electric Propulsion Vehicle

	Nominal altitude, ASL	Nominal speed, knots	Max. altitude, ASL	Max. speed, knots
Takeoff	0	45	0	60
Climb	Between 0 and 10,000 ft	45 to 130	Between 0 and 15,000 ft	60 to 175
Cruise	10,000 ft	130	15,000 ft	175
Descent	Between 10,000 and 0	130 to 45	Between 15,000 and 0	175 to 60
Landing	0	45	0	60

2.0 Airframe Model

The airframe model is that of the full-scale SUSAN aircraft and is built in MATLAB®/Simulink® (Ref. 3). This configuration, shown in Figure 1, is the initial configuration used for the quarter-scale model. Over time and potentially in stages, the airframe model could be modified to represent the tailless aircraft shown in Figure 2. The quarter-scale version will have a severely reduced flight envelope compared to the full-scale aircraft, roughly equivalent to that of a general aviation aircraft, as shown Table 1.

The full-scale SUSAN aircraft flight dynamics model is a 6-DOF real-time simulation that implements general rigid body equations of motion for the flight vehicle. Aerodynamic coefficients (lift, drag, moment) are determined via lookup tables from an aerodynamic database generated through medium-fidelity computational fluid dynamics (CFD) tools.

3.0 Airframe Scaling

The initial quarter-scale airframe model is simply a scaled version of the full-scale; it utilizes the same aerodynamic database, which was developed to include the tail. The subscale model was developed subject to the rigid-body dynamic scaling approach outlined in References 4 and 5. This method allows for dimensional, velocity, weight, time, and inertial scaling. The general equation for scaling is:

$$p_{subscale} = p_{fullscale} * \lambda^n \tag{1}$$

where p represents the parameter of interest, λ is the subscale to full-scale ratio, and n is the scaling factor. A list of scaling factors can be found in Reference 6. Some parameters, such as mass, require Equation (1) to account for air density:

$$p_{subscale} = p_{fullscale} * \lambda^n * \left(\frac{\rho_{fullscale}}{\rho_{subscale}}\right)^{-1} \tag{2}$$

where ρ is the air density at test altitude. Note that if both full-scale and subscale vehicles are at sea level, this ratio equates to one. While the dynamic scaling approach is considered valid for standard airframes, it is not considered an accurate method for scaling aero-propulsive interactions which are highly complex coupled phenomena. Thus, the current quarter-scale model does not account for the interacting forces or moments in its aerodynamic model.

Figure 4 presents a simplified diagram of the model implementation. The aerodynamic database, created for the full-scale concept aircraft, provides dimensionless coefficients to the appropriately scaled 6 DOF model. Likewise, the engine positions are adjusted to provide the appropriate forces and moments on the 6 DOF airframe. The figure is generic, i.e., the scale factors enable the model to represent the full-size aircraft or a reduced size version.

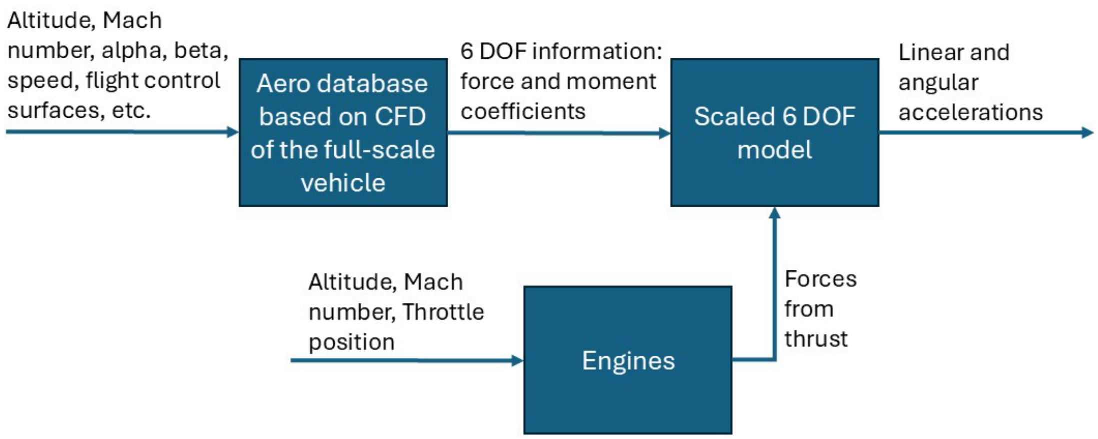

Figure 4. Simplified block diagram of the model implementation.

4.0 Powertrain Design

The quarter-scale powertrain design includes a DeltaHawk engine, and 16 electric ducted fans under the wing (Ref. 7), as well as a larger ducted fan in the tail. The electrical power system (EPS) can be divided into four major subsystems: main power generation subsystem, the tail electric engine and control subsystem, the wing power subsystems, and the wing electric engine and control subsystems.

The main power generation subsystem consists of a mechanical power source (DeltaHawk DHK 108A4 engine, rated at 180 hp at 2,600 rpm, running Jet A), which drives four electric machines in generator mode. The generators are controlled by AC-DC converters, which convert the AC input to feed the main propulsive busses at ±135 Vdc, or 270 Vdc total. These propulsive busses feed the tail electric engine and control subsystem, which consists of a DC-AC converter drive and the tail electric engine, as well as the wing subsystems (which are discussed in the following paragraphs). A high-level schematic of the main power generation subsystem and the tail electric engine and control subsystem is shown in Figure 5.

In addition to feeding the tail engine, the main power generation subsystem also feeds the wing power subsystems, as indicated in Figure 5. There are 16 wing subsystems in total, eight wing electric engines per side, each of which includes a pair of DC-DC converters. Each of these DC-DC converters reduces the incoming 135 Vdc to 24 Vdc. The goal is to maintain a bipolar bus, so the pairs of DC-DCs are configured to form a ± 24 Vdc bus, feeding a pair of batteries. One wing power subsystem, including converters and batteries, is shown in Figure 6.

Each of the 16 wing power subsystems feeds a single wing electric engine and control subsystem. These subsystems include a local battery, a DC-AC converter (to drive the wing motor), the wing motor itself, and the flap motors and controls. A schematic of a wing electric engine and control subsystem is shown in Figure 7.

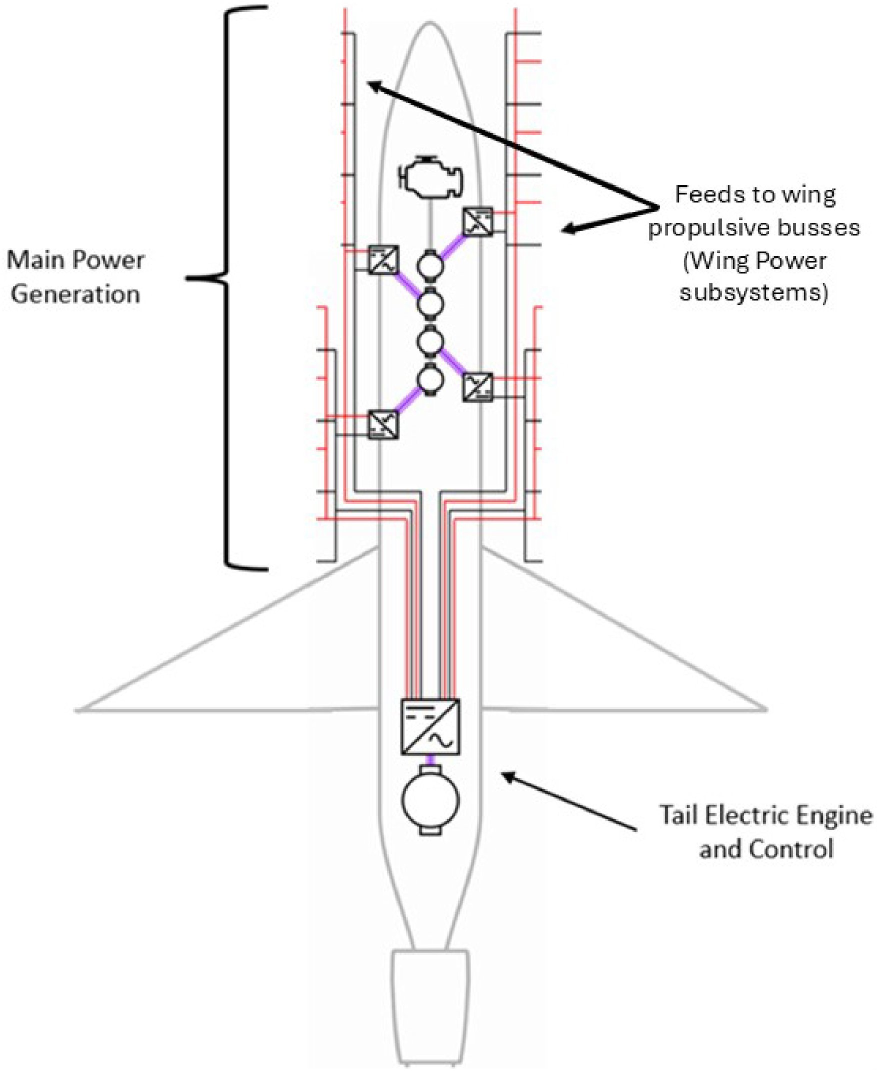

Figure 5. Main power generation and tail electric engine and control subsystems.

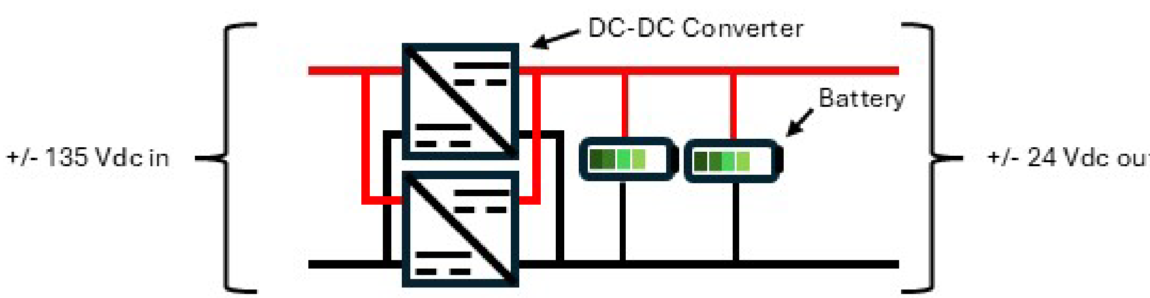

Figure 6. Wing power subsystem.

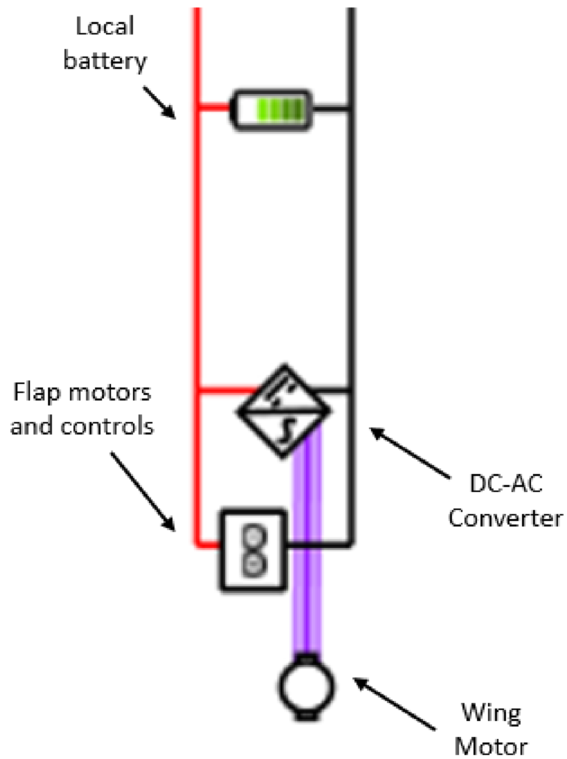

Figure 7. Wing electric engine and control subsystem.

The entire combined quarter-scale EPS is shown in Figure 8. The power system was designed to be flown, although a weight analysis has yet to be conducted.

5.0 Thermal Management System Design

A thermal management system (TMS) design was developed for the quarter scale vehicle and integrated with the power system design. Previous work focused on the full-scale SUSAN TMS and utilized a key performance parameter (KPP) approach for system sizing and mission analysis (Ref. 8).

The quarter scale TMS utilizes single-phase liquid cooling, rejecting to the outside air using a combination of ram-air and skin (or outer-mold-line) heat exchangers. The TMS layout is shown in Figure 9. Heat acquisition is through immersion cooling, wherein the coolant makes contact with current carrying devices, such as motor windings, power electronics, circuit boards, and bus bars. This method of cooling provides sufficient heat transfer to handle the large heat fluxes generated by the high power density components. Water was chosen as the coolant to enable rapid and low cost prototyping with a safe and non-toxic fluid. This requires that electronics be electrically isolated from the water via insulation and dielectric coatings. The main generator converter (MAGIC) is an exception in that it utilizes polyalphaolefin (PAO) with direct immersion cooling, as it was not designed to be water cooled (Ref. 9). This requires an additional liquid-liquid heat exchanger to transport heat from the PAO loop to the water loop.

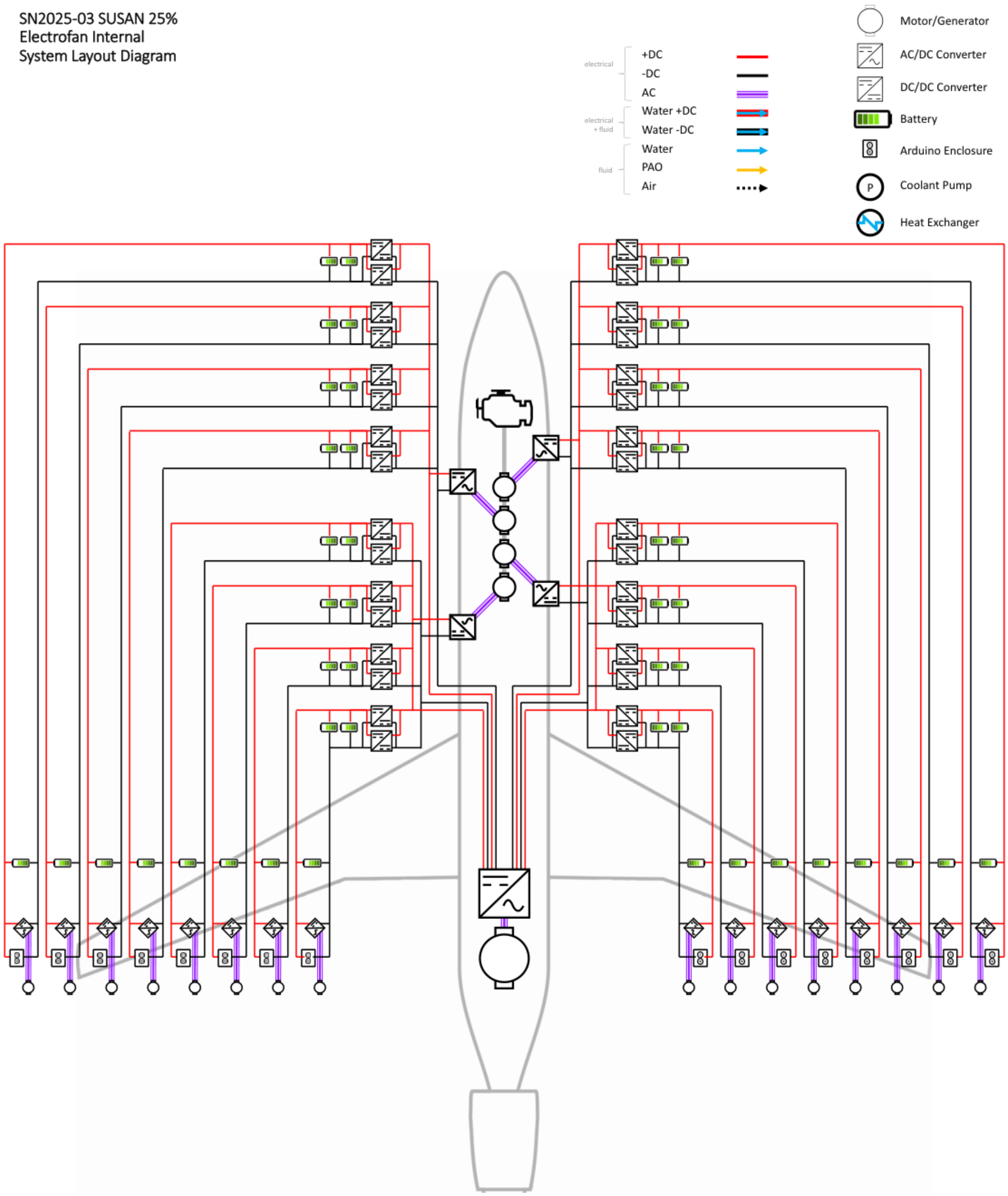

Figure 8. Quarter-scale distributed propulsion electrical power system.

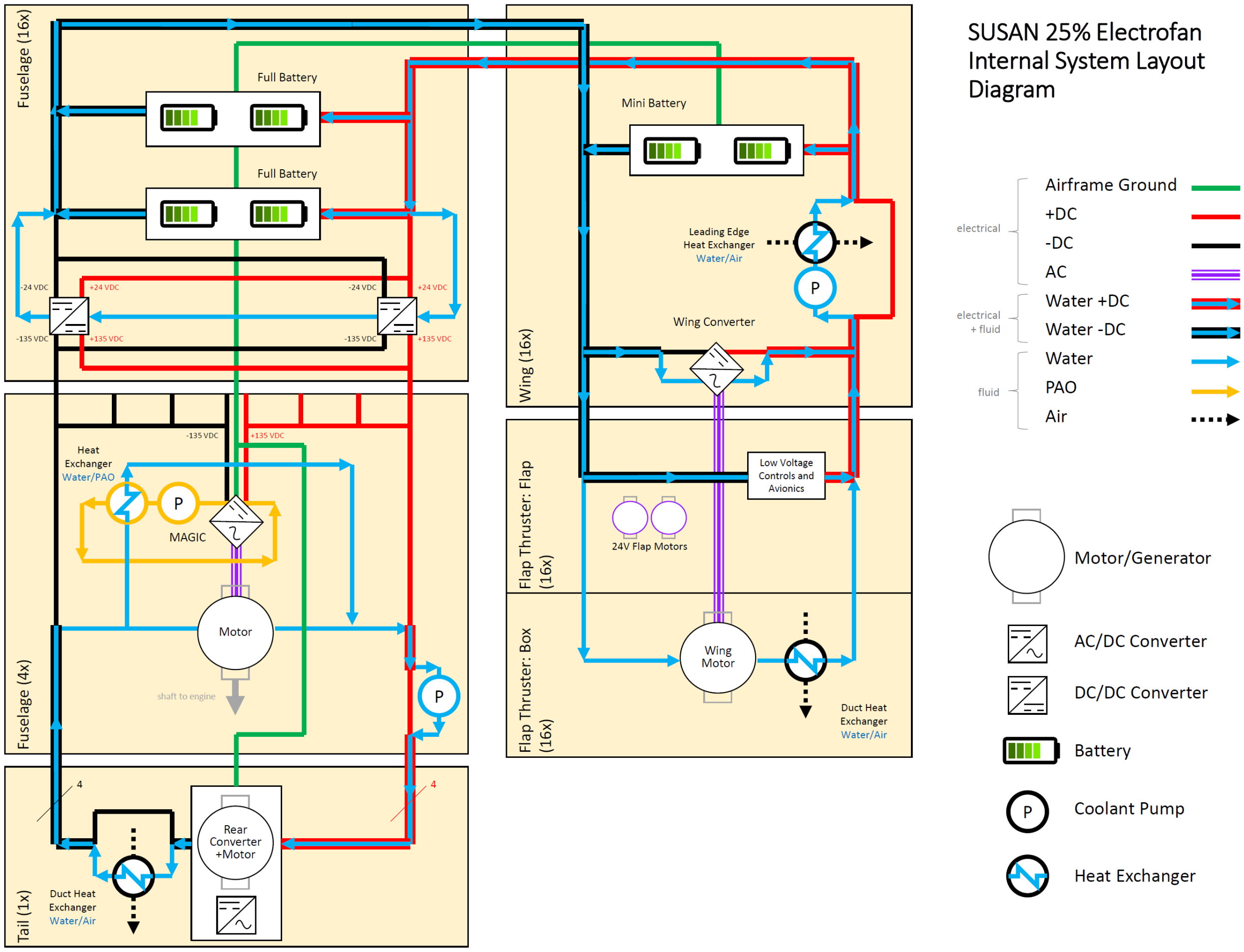

Figure 9. Quarter-scale distributed propulsion thermal management system diagram.

Similar to the full-scale SUSAN, the 25% scale TMS transports heat via liquid cooled electrical lines on the DC bus. This integration of the electrical and thermal distribution systems is predicted to be a net weight savings. The benefits are greater for longer lengths of lines, therefore this technology is only employed for lines running from the fuselage of the aircraft to the wings and from the fuselage to the tail. Lines that are predicted to be shorter, such as between motors/generators and their respective converters, are not liquid cooled. Implementation of this design creates an even tighter coupling of an already highly integrated thermal and electrical system that is typical for EAP. Because of this integration, the electrical components must be placed on the fluid loops in roughly the same relative positions as they are on the electrical circuits. Another advantage of this approach is that the redundancy and fault tolerance of the distributed electric propulsion system is maintained in the TMS. For example, a failure in a single wing coolant loop will not impact thermal management of components on the other wing or tail coolant loops. This redundancy in the TMS is an important factor to consider in the weight, power draw, and drag of a realistic hybrid-electric aircraft.

6.0 Software Tools

The electric fans are modeled using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) (Refs. 10 and 11). T-MATS is a NASA-developed library of Simulink® blocks that simplify the dynamic modeling, control design, and analysis of turbomachinery. The T-MATS wingfan models were matched to the physical fans described in Reference 7 using the T-MATS iDesign tool to convert the map from the full-scale SUSAN aircraft model to represent the physical ducted fans (Ref. 12). The fan model consists of two submodels to allow it to account for the full range of operation (Ref. 13). Because the T-MATS fan model only converges at higher or normal thrust producing speeds, a static model was used to represent low to very low power operation (Figure 10), resulting a small discontinuity as operation passes from one model to the other as the power level changes.

The DeltaHawk is an FAA certified, 2 stroke pressure scavenged, piston engine capable of delivering 180 hp at 2,600 rpm. The model of the DeltaHawk uses an efficiency map to relate input power to output power. Its input is fuel and its output is mechanical horsepower driving the shaft, thus specific fuel consumption (SFC) is used to represent the overall efficiency of the engine. Because it has a super charger and turbo charger, the effect of altitude is neglected, thus airflow isn't considered in the model. Figure 11 shows the efficiency map used in the model. The peak efficiency is in the high speed, high torque region where SFC is minimized; the least efficient is in the low torque region.

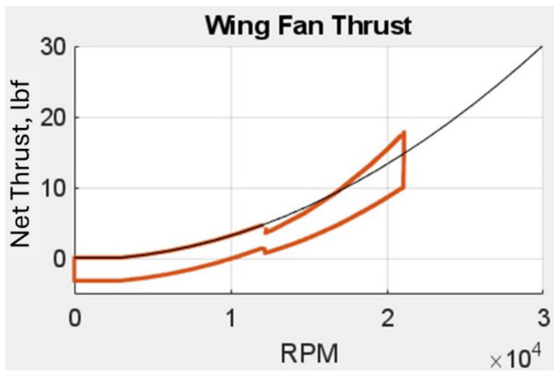

Figure 10. Wingfan thrust vs speed plot. The black curve comes from wind tunnel testing (Ref. 7), the orange represents two cases: upper is zero velocity (no drag) and lower is nonzero velocity (includes drag). Above about 12,000 rpm is the T-MATS model, below 12,000 rpm is the static model.

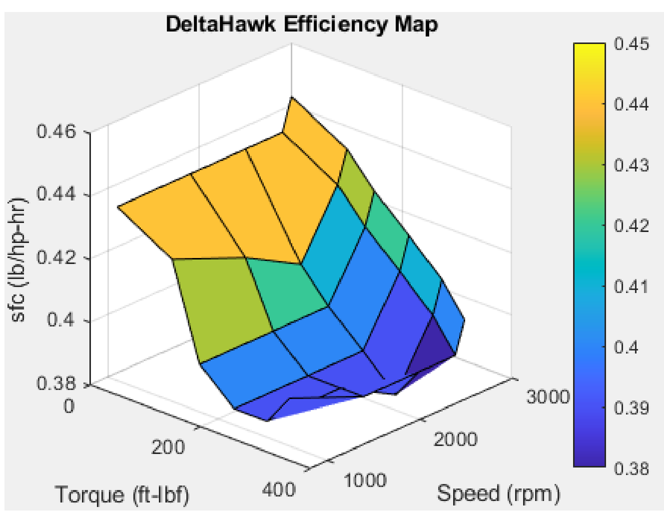

Figure 11. Efficiency map used in the DeltaHawk model. Lower SFC corresponds to higher efficiency.

The EPS and TMS are modeled using the Electrical Modeling and Thermal Analysis Toolbox (EMTAT) (Refs. 14 and 15). EMTAT is a NASA-developed library of Simulink® blocks that simplify the modeling of EPS 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 powertrain made over time can be accommodated fairly simply within the structure of an existing model.

The preliminary TMS model follows the design (Figure 9), but it does not yet capture the integration effects. This is demonstrated in Figure 12, which shows an example of the tail motor heat exchanger. In the model, water that has carried heat away from the motor enters the heat exchanger and is cooled by ambient air at the flight condition rather than air passing through the ducted fan. The cooled water continues its circuit while the heated air vents to the outside. It can be seen in the figure that temperatures track the motor power, indicated by Power Lever Angle (PLA), with a several second thermal lag.

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. An aircraft can be selected from a built-in fleet containing various aircraft types or one can be created using an application called Planemaker®, which is included. 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 is used for this application is a self-contained modular flight deck (MFD) that offers an immersive experience with a two-seat cockpit, motion base, and wrap-around out-the-window displays (Figure 13). It maps the pilot controls into the appropriate inputs to the X-Plane® software, and X-Plane® updates the pilot displays in real time and renders the scene. Although X-Plane® has the capability to simulate the flight dynamics of a variety of aircraft, that feature is not used directly in this research flight simulator application.

Additionally, a control panel was added to the Simulink® user interface that allows wingfans and generators within the model to be failed during simulated flights. This feature can be used to perform certification studies (Ref. 16), for instance.

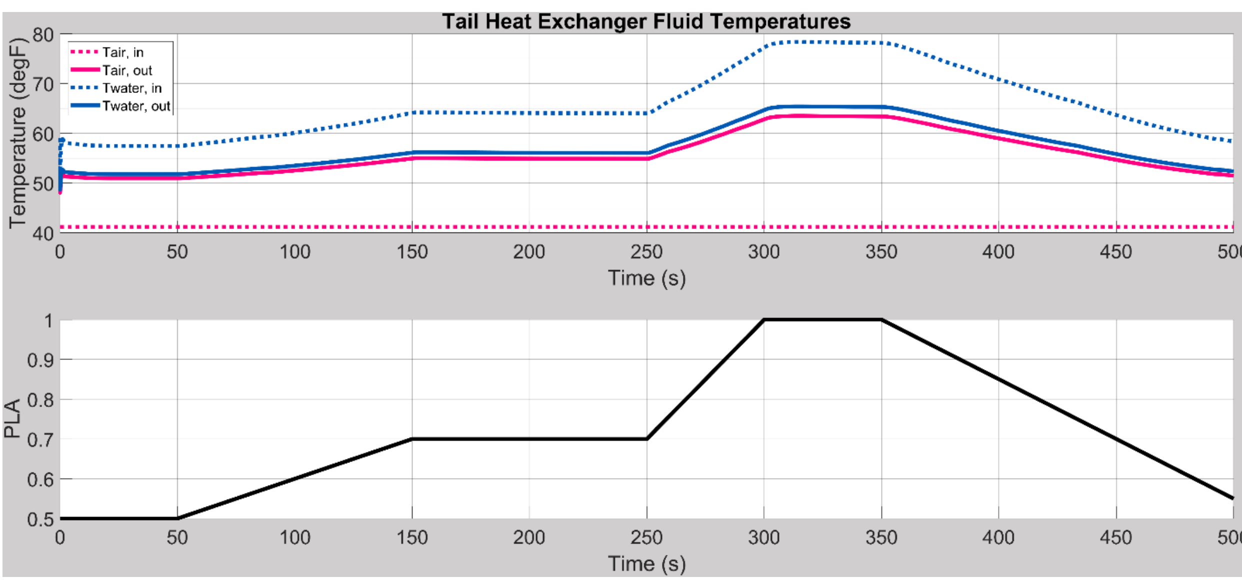

Figure 12. Tail heat exchanger thermal management simulation at altitude = 5,000 ft, Mach number = 0.2. Water heated by the motor is cooled by ambient air, which vents to the outside. The temperatures track the motor power with a slight lag.

Figure 13. Interior view of flight simulation test bed for piloted evaluations.

7.0 Integration

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

7.1 Integration of the Airframe Model with the Powertrain Model

The quarter-scale airframe flight dynamics model (aerodynamic database) and the powertrain model are created separately. The airframe model will have thrust vectors at the appropriate locations, which the powertrain model will supply. 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. The integrated model must run faster than real time to allow for real-time implementation in a flight simulator (Ref. 17).

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

The approach described in Reference 18 is used here. The flight simulator (Figure 13) uses X-Plane® to run the displays and to capture the pilot input. The aircraft model takes certain inputs from the cockpit, e.g., PLA and flight control surface commands, and returns aircraft position and orientation information required to render the out-the-window view, as well as data to be displayed to the pilot. The software plugins—the interface between MATLAB®/Simulink® and X-Plane®—handle the exchange of data at a frequency of 50 Hz. This is slower than the 66.7 Hz update rate of the simulation, so new information is passed from the simulation to the cockpit each time. It is sufficient to provide a smooth visualization for the pilot, and certainly fast enough to fully capture the pilot inputs.

8.0 Pilot Interface

A bonus of utilizing a flight simulator for this work is that it not only enables but requires the development of a pilot interface. Since a physical quarter-scale vehicle would be remotely piloted, the requirements for information available at a ground station need to be defined. The flight simulator implementation provides the opportunity to define the data and display requirements.

Here the displays developed for the full-scale vehicle (Ref. 19) were modified so they are appropriate for the quarter-scale powertrain (Figure 14). This meant removing the emergency battery information as well as replacing the turbofan engine data with that of the tailfan. Otherwise, the displays are very similar to those developed for the full-scale aircraft, including the primary flight and multi-function displays, the wingfan speed, and battery status.

9.0 Flight Evaluation

The preliminary flight simulator implementation, now complete, was used to evaluate aircraft performance to determine areas of modeling and/or design improvement. Takeoff and landing, climb, handling, etc., were evaluated by the pilot. The testing was performed in an immersive, FAA-certified, piloted flight simulator (Figure 13). The aircraft is stable and generally handles well, but appears to be underpowered, although the issue might be that the airframe has too much drag. The distinction here is that the powertrain model was built to match the quarter-scale design and was subsequently paired with a scaled down full-size model with an empennage, which may be the cause of the discrepancy. In any case, the pilot attempted various maneuvers to evaluate the performance of the current integrated model. The pilot could land and take off, generally getting speed down to between 50 and 60 knots just before touchdown. The aircraft could reach a reasonable speed of about 115 to 120 knots, at various flight conditions, at least temporarily, but had difficulty climbing faster than about 100 ft/min consistently, which is much slower than expected. When the simulation was initialized at 5,000 ft, the pilot could climb and was essentially able to maintain level flight at 5,300 ft, 120 knots, with a small amount of porpoising (about ± 80 ft/min vertical) as no autopilot was present. In several trials, the simulated flight was initialized at higher altitudes (7,500 ft, 10,000 ft) and 130 knots. The pilot attempted to maintain level flight by increasing angle of attack (AoA), causing a loss of airspeed, and eventually a slow descent.

Figure 14. Flight displays.

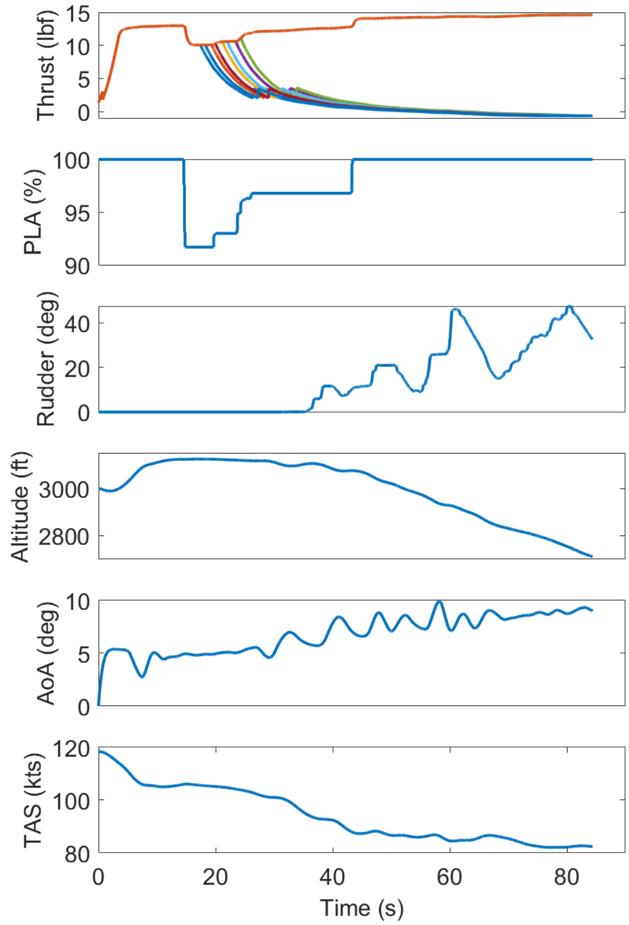

Figure 15. Flight segment in which left wingfans fail and pilot attempts to maintain level flight.

Powertrain faults can be injected into the flight simulator model, specifically individual generators or fans can be failed. Figure 15 shows a case in which the pilot stabilized the aircraft at about 3,125 ft, 105 knots true airspeed (TAS), full power, and about 5° AoA. The pilot then reduced power slightly and after about 3 sec, the eight left-side wingfans were failed sequentially over about 7 sec while the right side continued to operate normally. The pilot added rudder to counteract the thrust asymmetry and tried to maintain altitude and airspeed by increasing AoA and PLA. However, both altitude and TAS began to drop. The pilot continued to increase AoA, and although the plane remained in a steady descent, AoA leveled out at nearly 10° and TAS stabilized at about 82 knots. The discontinuity in thrust related to the submodel switching is visible in the top plot as the fans pass through about 2 to 3 lbf. The inertia of the aircraft would likely prevent the pilot from noticing this discontinuity.

10.0 Discussion

The model of the quarter-scale distributed electric propulsion vehicle captures significant features of the design, including those related to aircraft and powertrain performance. Although the model can reach only a portion of the flight envelope, it provides a way to test various features of the design in a fairly realistic environment as well as the interaction of the subsystems. Furthermore, it can help to expose potential shortcomings of the design or the integration since subsystem models can be individually validated (Ref. 20).

The example points out an interesting situation related to the design of the powertrain. In the full-scale design, the connections are interleaved such that each generator drives four wingfans selected to avoid thrust asymmetry in the case of a generator failure. In the quarter-scale design, each generator powers four contiguous wingfans (Figure 8), although this could be changed in a future iteration. As it stands, though, the type of failure in the example—all wingfans on one side lost—is not as unlikely as it would be with a design similar to that of the full-scale powertrain. Because the quarter-scale vehicle is envisioned to have no empennage, it would rely on the wingfans for maneuvering. Previous work demonstrated the use of differential thrust to replace the rudder function even in the presence of multiple fan failures (Refs. 21 and 22), which would be difficult with thrusters available on only one side. This is somewhat alleviated by the plan to incorporate thrust vectoring, but that remains future work. In general, loss of power and loss of control concerns are to be expected in a passenger aircraft with this architecture. The full-scale SUSAN concept was designed with multiple thoughtful features to help address certification questions, and the quarter-scale vehicle, should it be built, provides a means to examine them further.

11.0 Conclusion

The model, although functional, is still preliminary. There are many modeling and control improvements to be made, as pointed out in the paper. In particular, the model does not operate as expected throughout the flight envelope, although more minor features, such as thermal management system integration and wingfan behavior, must also be addressed. This effort demonstrates the complexity of developing a complete system model of this magnitude and fidelity, especially given that the quarter-scale vehicle design has not been finalized. Aside from the fact that not all components are thoroughly characterized, implementation and integration of the individual subsystem designs provides a working aircraft model that does not perform fully according to specification. Use of a tailless airframe model could improve the performance by reducing drag, but a thrust vectoring system design would need to be incorporated and tested. Nevertheless, leveraging the yearslong iterative design process the original SUSAN Electrofan concept went through gives a good baseline for the quarter-scale distributed electric propulsion vehicle design and the model developed from it. Further testing with the model can inform any future iterations of the quarter-scale design.

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