Mission Profiles for the SUSAN Electrofan Concept

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The SUbsonic Single Aft eNgine (SUSAN) Electrofan is a novel aircraft concept which utilizes a single aft-mounted engine, electrified aircraft propulsion, an emergency backup battery, as well as state-of-the-art aerodynamic design and thermal management systems to reduce the overall environmental impact of the aircraft. Mission profiles, which define the aircraft state and flight characteristics throughout various phases of flight, are an important component of aircraft conceptual design. These defined characteristics serve as sizing requirements design constraints. By defining the mission profiles to be within airworthiness certification standards and regulations, aircraft designers can ensure the concept is developed within compliance of these regulations throughout the design process. This paper presents mission profiles for the SUSAN Electrofan aircraft, including the basis for defining the characteristics required during each phase of flight.

I. Introduction

As novel aircraft configurations and associated technologies are developed, the planned mission goals serve an important role in determining the requirements the design must meet. The identified mission, including the design and the economic mission lengths, as well as the aircraft class, are essential in establishing the size, endurance and range of the aircraft. However, with any aircraft, off-nominal mission profiles, such as those accounting for engine failures, also have a dramatic effect on the aircraft sizing. For novel aircraft designs, the off-nominal mission profiles can have an even greater impact.

In recent years, conceptual aircraft design has required increasingly detailed modeling of flight and mission profiles to support sizing analysis and design optimization studies [1–3]. While cruise conditions are an important sizing point, other aspects of the mission profile (such as takeoff and climb) and off-nominal mission profiles often are the bounding factors in aircraft design optimization [1, 2]. For the SUbsonic Single Aft eNgine (SUSAN) aircraft, identifying and defining these mission profiles and flight regimes is particularly important. Research has also been conducted to better understand how to best utilize these mission profiles throughout the conceptual design process, particularly for short-haul aircraft [1, 2, 4].

NASA has experience studying advanced hybrid electric concepts, including the Single-Aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion (STARC-ABL), which utilizes hybrid electric propulsion and boundary-layer ingestion to reduce fuel consumption [5]. Defining mission profiles and requirements can also aid in the airworthiness certification approach during conceptual design, by ensuring that predicted design performance is compliant with established regulations and standards [6].

This paper provides a brief overview of the SUSAN Electrofan concept in Section II, which is presented in more detail in Machado et al. [7] and Chapman et al. [8]. The main phases of flight are then defined in Section III, along with the relevant regulatory standards for each phase. Next, mission profiles are presented in Section IV for the

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SUSAN Turbofan aircraft, beginning with the nominal mission profile, which have an impact on the sizing or required performance of the aircraft. Failures of either the turbofan or electric engines during various stages of flight are considered, and the initial impact those failures have on the design are presented. Finally, concluding remarks and related ongoing work are shared in Section V.

II. SUSAN Electrofan Concept

The SUSAN Electrofan concept, shown in Figs. 1a and 1b, is designed to reduce cost, emissions, and fuel usage by utilizing electric aircraft propulsion. The aircraft is designed to fit within the existing commuter transport market, with 180 passengers and a design range of 2,500 nautical miles at a cruise altitude of 37,000 feet [9].

(a) SUSAN Electrofan concept during takeoff.

(b) Side view of the SUSAN Electrofan concept.

Fig. 1 Artist renderings of the SUSAN Electrofan concept, showing the wing-mounted electric engines, aft turbofan engine, and T-tail.

The SUSAN concept utilizes a combination of electrified aircraft propulsion and advanced propulsion airframe integration. By utilizing a single fuel-burning traditional turbofan and 16 wing mounted electric engines, the benefits of distributed electric propulsion can be realized while simultaneously retaining the airport infrastructure of current aircraft, with no battery charging or swapping required. To complete this mission, the aircraft contains small secondary batteries used to power the electric engines as well as larger single-use primary batteries that are used in the event of turbofan failure [9, 10].

III. Critical Phases of Flight

A typical transport aircraft flight mission profile can be broken into several critical phases, each of which have their own flight characteristics and performance requirements, based on existing regulations. However, the aircraft must remain controllable and maneuverable during all phases of flight, as per the code of federal regulations in 14 CFR 25.143 [11].

Takeoff

The takeoff phase is from the moment the aircraft begins its initial ground roll to the point it is 1,500 feet above the runway surface or has completed transition to the enroute configuration. This phase of flight is governed by 14 CFR 25.105-25.115, which importantly define critical speeds and the required takeoff path climb gradient [11]. Because of the novel hybrid propulsion system used, the takeoff flight phase is of special interest due to the critical engine inoperative requirement of 14 CFR 25.111, which requires the aircraft to continue takeoff after loss of critical engine above a certain speed [11]. For the SUSAN concept, this requirement means that the electric engines must produce enough thrust for takeoff, which is discussed in more detail in Section IV.B.

Climb

The climb phase of flight, also known as the initial climbout, can often include multiple segments at different climb rates, such as an initial high rate of climb to get out of the immediate airport vicinity, followed by an optimized climb rate to reach the cruising altitude. In addition to the climb rate requirements of 14 CFR 25.117 and 25.121, controllability throughout the climb phase is also required [11].

Cruise

While the cruise phase can typically be the longest duration component of a mission profile and directly affects the sizing of the aircraft, it can also be the phase with the least changes to the aircraft state and dynamics. In the cruise phase, the aircraft weight will change due to fuel consumption, however, given the use of electric propulsion, the weight change during the flight will be lower compared to conventional configurations. High speed characteristics and design airspeeds, governed by 14 CFR 25.253 and 14 CFR 25.335 respectively, are also important [11].

Descent

The descent phase of flight is similar to the cruise phase of flight, with minor changes to configuration as well as reductions in speed and altitude.

Landing

Similar to takeoff, landing phase carries several risks due to the high operating workload, the proximity to the ground and risk of failure. CFR 14 25.125 states the requirements for landing of transport aircraft, notably defining the landing distance [11]. For the SUSAN Electrofan aircraft, it is estimated that the landing distance will be similar to other transport category aircraft, such as the Boeing 737 MAX 8. Ground handling conditions during taxi, specified under 14 CFR 25.233, are particularly relevant in off-nominal mission profiles [11].

IV. Mission Profiles

This section will step through the mission profiles for the SUSAN Electrofan aircraft, noting the phases of flight they include, and focusing on the aspects that make these profiles important from a design or airworthiness certification perspective.

A. Nominal Mission Profile with Reserve Requirement

The nominal mission profiles are shown in Fig. 2, which include a 2,500 nautical mile design mission and a 750 nautical mile economy mission, each at a design payload of 162 passengers (90% load factor). The former is used to size the aircraft components and subsystems, determining many of the design weights of the aircraft, while the latter represents a typically flown mission used to evaluate aircraft performance, fuel burn, and emissions.

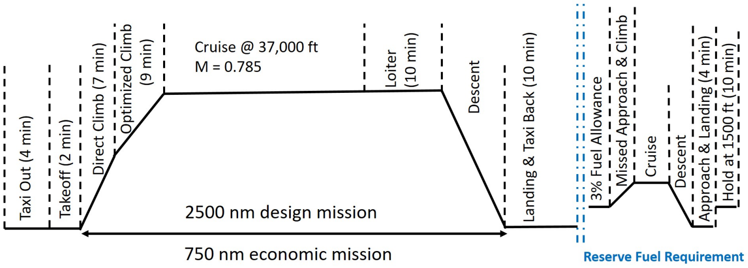

Fig. 2 Nominal mission profile for the SUSAN Electrofan concept with included reserve fuel requirements. [6]

Nominal operating conditions include a cruise Mach number of 0.785 and an initial cruise altitude of 37,000 ft in standard day atmosphere conditions. The propulsion systems are sized for a maximum top-of-climb thrust of 11,500 lb and a maximum takeoff thrust of 54,300 lb, each based on a Boeing 737 MAX 8-like aircraft. The power systems are also sized not to exceed specified limits, namely, 13,410 hp (10 MW) and 26,820 hp (20 MW) at top-of-climb and takeoff, respectively. These limits were set based on estimation of future power system capabilities.

These parameters are implemented within an engine deck modeled with NASA's Numerical Propulsion System Simulation (NPSS) which provides a consolidated hybrid electric propulsion system model. The NPSS was used to determine thrust and rates of fuel consumption for a given Mach number, altitude, and throttle [12, 13]. The Weight Analysis of Turbine Engines (WATE++) tool was used to calculate weights for engine subsystems. This engine deck and subsystems weights are used with a conceptual multidisciplinary design and analysis framework to size the aircraft systems and evaluate nominal aircraft performance [14]. Reserve fuel was also included to satisfy a 100 nautical mile diversion and 45 minute hold based on 14 CFR Part 121 for regional aircraft [11].

B. Loss of Turbofan Engine During Takeoff

For commercial aircraft, many of the critical design aspects are derived from the mission elements associated with engine out climb performance. For a multi-engine configuration, the aircraft must still be able to complete the takeoff, maintain appropriate speed, and meet a specified climb gradient following a critical engine failure at or above the specified engine failure velocity V_EF. In case of a turbofan failure, the SUSAN aircraft operates entirely under electrical power using the backup battery, which is sized to support the power requirements of takeoff. The aircraft is designed to enable climb at a reduced rate and cruise at a reduced altitude and speed, compared to the nominal case, providing the aircraft suitable time to execute a safe landing with a maximum flight range of 300 nautical miles.

Commercial aircraft are required by 14 CFR 25.121 to meet a safe One Engine Inoperative (OEI) climb gradient for obstacle clearance at maximum gross weight [11]. The required climb gradient is dependent on the number of engines and other factors (typically around 3% positive gradient); however because the SUSAN configuration was not envisioned in the existing OEI climb requirements, the applicable requirements for OEI climb need to be negotiated with the civil authorities. It is reasonable to assume that the SUSAN aircraft would be required to demonstrate the required OEI climb solely using the electric propulsion system if the worst case scenario for loss of thrust on the single tail-mounted turbine is considered. Additionally, cases such as degraded distributed electric propulsion (DEP) system performance, bird strike on a series of propulsors, or other failure modes should also be demonstrated under OEI climb criteria.

Because this OEI climb requirement is vital in the overall design of the SUSAN propulsion systems for sizing the turbofan and the DEP sytem, it is reasonable, during preliminary sizing, to compare the SUSAN Electrofan concept to an existing aircraft of similar size and capability, like the Boeing 737 MAX 8. The process for OEI sizing is as follows:

1) Using Boeing 737 MAX 8 aircraft climb performance values, estimate comparative climb performance and the total power required to meet the OEI climb gradient.
2) From that power estimate, and assuming a 50/50 split between the two engines, estimate the power required for OEI climb.
3) Adjust the 50/50 split to estimate the power required assuming the SUSAN aircraft has a 65/35 split between the electric engines and the single fuel-burning turbofan.

From the information available on the Boeing 737 MAX 8, level flight uses an estimated 9.2 MW and a typical climb uses roughly 12.2 MW of power with both engines running at 85% [15, 16]. Using these numbers, a simple estimate of 100% power can be made of roughly 14.4 MW for climb. Typically half of this would be assumed for OEI climb, however, SUSAN is being designed so 65% of the thrust is being provided by the wing-mounted electric engines and 35% by the turbofan in cruise. For OEI the turbine would still need to be able to meet the power requirements similar to half the estimated power of the Boeing 737 MAX 8. This dictates the turbine should be sized to meet the 7.2 MW for OEI climb at 100% power. Maximum Continuous Thrust (MCT) for OEI rated power would likely be less than 100% due to engine limitations, but 100% is used for this preliminary sizing exercise for conservativeness.

Even though the distributed electric propulsion system is planned to provide 65% of the thrust for the aircraft in cruise, during OEI climb the system will still need to provide the full 7.2 MW, or half the 100% normal climb energy produced by two engines for the Boeing 737 MAX 8. This calculation shows that for the SUSAN design to meet a similar OEI climb performance gradient to that of the Boeing 737 MAX 8, the electric engines have to provide 7.2 MW of energy for the duration of the climb to a safe altitude.

Many existing jet engines have roughly a five minute MCT limit, and the climb to a safe altitude in the event of an OEI climb depends on the departure procedure the aircraft is following, along with the actual limits of the turbine and DEP system. It is reasonable to assume a five minute limit for this high level of energy, so the OEI climb would require the DEP to generate 7.2 MW for five minutes as a maximum requirement, then reduce to a thrust setting for continued safe flight and landing after the OEI climb. The final battery sizing for the primary battery used in the SUSAN concept is an area of ongoing research.

C. Loss of Electric Engine During Takeoff

Although the loss of a single electric engine would have a smaller effect on the overall performance of the aircraft, a good practice is to design for this failure and ensure regulatory requirements are met. As shown in Fig. 3, in the event of a loss of a single electric engine at or above the specified failure velocity ($V_E F$), the SUSAN concept is designed to climb normally and reach the nominal cruise altitude and speed. However, to minimize the risk of additional failures, the remaining flight time will be limited (initially set as 1 hour), as shown in green. With the design cruise speed (Mach of 0.785), this is approximately equivalent to 600 nautical miles, close to the assumed economy mission. Thanks to the redundancy in electric engines, the SUSAN aircraft could potentially still complete the intended mission, even in the event of an electric engine failure.

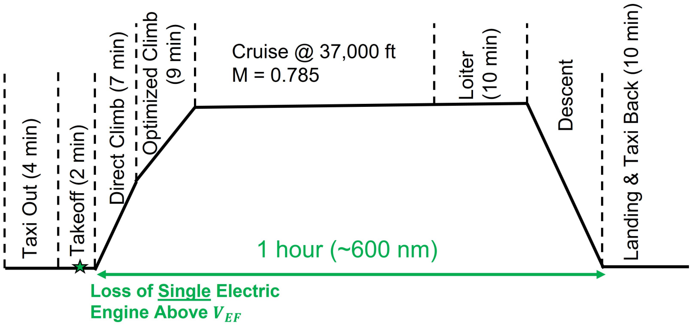

Fig. 3 Mission profile for the SUSAN Electrofan concept in the event of single electric engine loss at or above final takeoff velocity.

Multiple electric engines could fail during takeoff, either due to bus failure or bird strike. With the bus configuration described in Jansen et al. [9], a single bus failure causes loss of four electric engines, balanced across the aircraft with two failed electric engines on each wing, to reduce any adverse yaw or roll effect [9]. A bird strike could damage any number of electric engines on a given wing, from a single engine to all eight. Using the same calculations given in Section IV.B, the remaining electric engines and turbofan must be able to produce at least 7.2 MW of energy to allow a safe takeoff. The loss of electric engine cases have been identified as an area of future work and analysis.

D. Loss of Turbofan Engine During Cruise

Turbofan failure during cruise, resulting in the loss of both thrust and electric power, is illustrated in the modified mission profile shown in Fig. 4, where the portions of flight using solely electric power are indicated in orange. Due to the significant thrust contribution from the turbofan, the aircraft would perform an emergency descent, allowing the aircraft to fly at the optimal altitude and velocity to an alternate airport. Using the assumptions and analysis provided in Section IV.B and assuming that cruise flight uses no more than 50% of total thrust available, then the electric engines would need to provide approximately 3.6 MW in the one engine inoperative case. Based on the reduced electric-only flight speed, the 30 minutes of flight time equates to a maximum of 300 nautical miles in range, although the exact range will be determined in a further analysis.

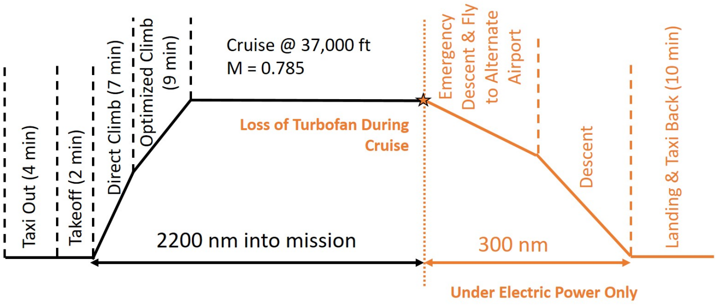

Fig. 4 Mission profile for the SUSAN Electrofan concept in the event of loss of the turbofan during cruise.

E. Loss of Electric Engines During Cruise

The loss of a single electric engine during cruise is not as significant as the loss of the turbofan. Figure 5 shows that with the loss of a single electric engine, the aircraft is designed to be able to continue cruise at the nominal mission altitude and speed, for no longer than one hour, as indicated in green. With a nominal mission cruise Mach of 0.785, one hour of flight time is equivalent to approximately 600 nautical miles. In most cases, the SUSAN concept is expected to perform the intended mission in the event of a loss of a single electric engine during cruise.

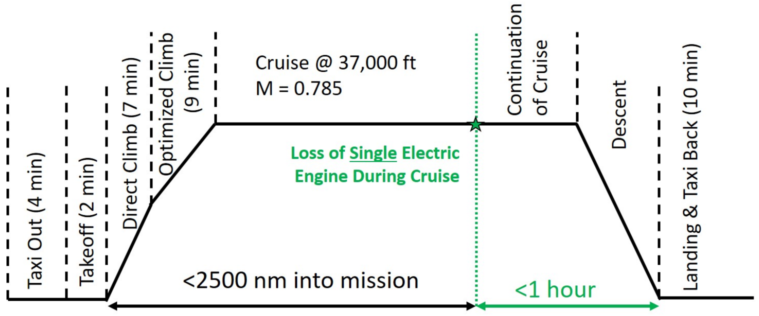

Fig. 5 Mission profile for the SUSAN Electrofan concept in the event of loss of a single electric engine during cruise.

As with takeoff, multiple electric engines could fail during cruise flight, due to bus or generator failure [9]. Similarly to the loss of turbofan during cruise profile, it is expected that the remaining engines and turbofan would need to provide around 3.5 MW of power to maintain cruise in the case of failure of one or more electric engines. However, due to the redundancy of the electric engines and the lower thrust required for cruise compared to takeoff, it is expected that this scenario will not be a major design driver, but it is an area for future research.

V. Summary and Future Work

Mission profiles with major impact to the sizing and trade space exploration were presented for the SUSAN Electrofan Aircraft. These profiles detail the flight characteristics required at each of the critical phases of flight, including takeoff, climb, cruise, descent, and landing. Initial analysis for the nominal mission profile, including a first order sizing estimate for the propulsion system and nominal aircraft performance was conducted. For the case in which the turbofan fails during takeoff, preliminary sizing was conducted to estimate the thrust required to enable takeoff using only the wing-mounted electric engines. Future work will include analysis of scenarios where one or more of the wing-mounted electric engines fail during takeoff or cruise and the impact that will have on performance and reliability.

By utilizing airworthiness regulations and standards to help define these flight characteristics, conceptual designers can ensure that the aircraft's predicted performance will meet compliance throughout the flight operating envelope. Because of the novel configuration of the SUSAN Electrofan aircraft, ensuring adherence to the regulations affects not only the size of the aerodynamic and propulsion systems, but also the electrical subsystems and operating procedures as well. As the SUSAN Electrofan design is finalized, future work will compare predicted performance to the required metrics included in the Code of Federal Regulations. Gaps associated with these regulations will be identified to ease the certification process of the SUSAN Electrofan aircraft and other similar future aircraft.

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