EXPERIMENTAL EVALUATION OF TRANSIENT AND STEADY-STATE CHARACTERISTICS OF A 180KW TURBOELECTRIC-AIRCRAFT TESTRIG

By

JOSHUA DRAKE

Bachelor of Science in Electrical Engineering
Oklahoma State University
Stilwlater, Oklahoma
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Thesis Approved:

Dr. Sheng

Thesis Advisor

Dr. Rouser

Dr. Third Reader

Dr. Outside Member

Name: JOSHUA DRAKE

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Abstract:

This thesis presents the experimental results of a turboelectric-aircraft power system operating under two electrical configurations. Hybrid turboelectric power systems enable increased versitility over their singularly hydrocarbon fuel or electrically based counterparts through the combination of their advantages: energy density in the case of combustion power systems, and power density in that of electrical systems. However, much of the research pertaining to such hybrid systems has been analytical, leaving a need for implementation and experimentation to characterize operating performance. The testrig assembled to undertake this work is comprised of a Cessna-172 airframe, a modified 180kW PBS-TP100 turboprop, and the components necessary to create two electrical configurations. The first of these configurations involved the use of a low system voltage, battery augmentation, and an inductive load in the form of electic motors; whereas the second configuration used a high system voltage, a variable-resistive load, and electrical power sourced exclusively from a turbine-driven generator. Custom electronics were fabricated to aid in the control of the variable-resistive load as well as for protection of the battery. The objective of the studies conducted on this system have been to evaluate the transient and steady-state performance of turboelectric aircraft under various engine and electrical load conditions. Configuration one was tested by varying electrical throttle at maximum engine throttle, whereas configuration two was tested through repeated variation in electrical load under four fixed engine throttle points. Engine operation data was acquired from every test including output shaft torque, speed of the free and gas turbines, and combustion gas temperature, while voltage, current, and power data was recorded at different locations within the electrical systems. Tests conducted on the first configuration showed 17kW of peak electrical power: 4kW from the generator and 13kW from the battery; while 142kW of mechanical power was transfered from the turboprop. Test two demonstrated consistent waveforms accross all four turbine throttle points, with peak power output reaching 11.5kW from the generator, and XXXXkW from the engine. Observations from these tests highlight the importance of capacitance to hybrid powertrains, the forces induced on turbine engines by electric load, and functional safety considerations in the design and operation of hybrid systems. This thesis provides insight into practical implementation of turboelectric power systems for future electrified aircraft.

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BACKGROUND

2.1 Turbine Engines

A cursory understanding of turbine engines is necessarry to contextualize this work, as their improved power to weight ratio and performance at altitude when compared to piston engines make them an ideal choice for use in hybrid electric aircraft. The following is a description of how a general jet engine with a single inlet and exhuast functions. This description corresponds to the station numbering found in 1 and is applicable to the subcategories of turbine engines discuessed later.

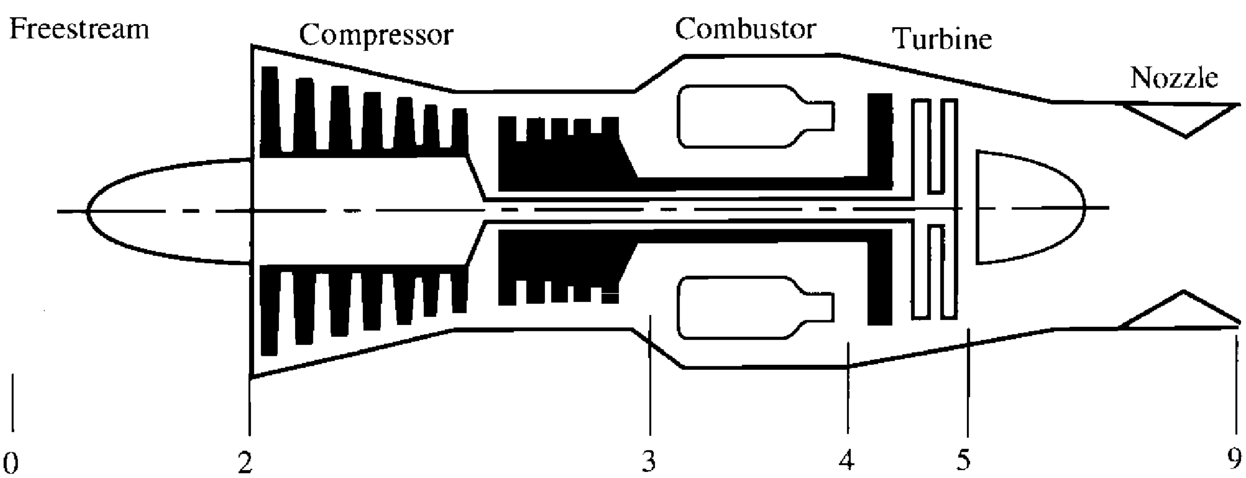

Figure 1: Ideal Turbojet with station numbering

The Inlet is the first section of the gas turbine engine, denoted by station numbers 0-2, and its operation and design are described in terms of the efficiency of the compression process, the external drag of the inlet, and the mass flow into the inlet. [7] Inlet design is most heavily influenced by whether the air entering it is subsonic or supersonic. Subsonic inlet design is simple, and typically involves selecting an operating velocity at which air compression is most efficient at the expense of performance at other velocities. Supersonic inlets must take the shockwaves endemic to supersonic flow into account for optimal performace. This is accomplished by adjusting inlet geometry to reduce flow velocity while adding as little weight to the system as possible. Variable inlet geometry will allow for increased efficiency accross many velocities.

Compressors, denoted by station numbers 2-3, increase the pressure of the flow obtained by the inlet such that the combustion and exhaust processes can be conducted more efficiently. Increasing the pressure of an initial volume of air results in the reduction of its volume, allowing for the combustion of the air/fuel mixture to occur within a smaller volume than it would otherwise. Turbine engines most commonly employ centrifugal or axial compressors. Figure 1 appropriately depicts an axial compressor in the makeup of the common turbine engine by virtue of their superiority. However, centrifugal compressors find use in smaller, less expensive engines due to their simple design. Centrifugal compressors are comprised of an impeller, which serves to increase flow velocity through rotation; a diffuser, which decreases the velocity of the flow thereby increasing its pressure; and a manifold which directs the compressed air into the combustor. Axial compressors are made of a series of stator vanes and rotor blades that are concentric to the axis of rotation. Each set of these stators and rotors is referred to as a stage. "The flow path in an axial compressor decreases in cross-sectional area in the direction of flow." [?] Each stage of the compressor results in an increase in air density. Thus, multiple stages are used in the design of high compression ratio turbine engines. Many turbines, including that which is depicted in figure 1, are equiped with dual axial compressors. Dual axial compressors allow for a more uniform loading of compressor stages, as well as for improved flexibility in the balancing between the initial and later stages.

The combustor, as illustrated in figure 1 between station numbers 3 and 4, is responsible for burning a mixture of compressed air and fuel and delivering the resulting exhaust gases to the turbine stage at a consistent temperature. The air that enters the combustion chamber is characterized as either primary air, meaning that it mixes with fuel and burns, and secondary air, which cools the extremity of the combustion chamber as well as exhaust gases to ensure optimal temperature within the turbine. The air to fuel ratio varies from 30 to 60 parts of air to one part of fuel by weight, depending on the design and type of engine. [7] The types of combustion chambers found within tubine engines are can, which consist of multiple circular chambers arranged in a similarly circular fashion; annular, a large single chamber design around a center casing; and can-annular, a combination of the previous architectures in which can chambers are organized within an annular cavity.

The turbine section of the engine, denoted by station numbers 4 through 5, is responsible for taking the energy generated in the combustion chamber and turning it into shaft horsepower to drive the compressor stages and external loads. Almost 75 percent of the energy generated from the combustion process is required to drive the compressor alone.[7]The axial-flow turbine is similar to the axial compressor, and is likewise comprised of a series of stages of rotors and stators. However, the turbine has the opposite effect of the compressor: it turns the energy contained within flow into shaft rotation. The stage quantity of the turbine section of a given turbine engine is typically lower than that of its compressor, as the flow is expanding rather than compressing. Axial turbines are either impulse design, which maintain flow velocity across their rotor and decrease pressure across their stator, whereas reaction stages increase pressure across their rotor blades and direct flow within their stator. Most turbines use a combination of these two stage designs, and must be dual or split commensurately with the design of the compressor.

The final stage of the turbine engine, the exhaust nozzle, denoted by station numbers 5 through 9, is responsible for increasing the velocity of the exhaust gas before discharge such that ample thrust can be generated by the engine. Ideally, the exit pressure of the flow leaving the nozzle should equal ambient pressure, otherwise the engine will operate less efficiently than it is capable. Nozzles are typically either convergent, or convergent-divergent, meaning a convergent duct followed by a divergent duct. Simple convergent ducts are used in the case where the ratio of turbine exit pressure to nozzle exit pressure is less than 2. The convergent-divergent duct is employed in instances where this nozzle pressure ratio is in excess of 2. Such ducts incorporate more sophisticated aerodynamic features and variable geometry in certain applications.[7]

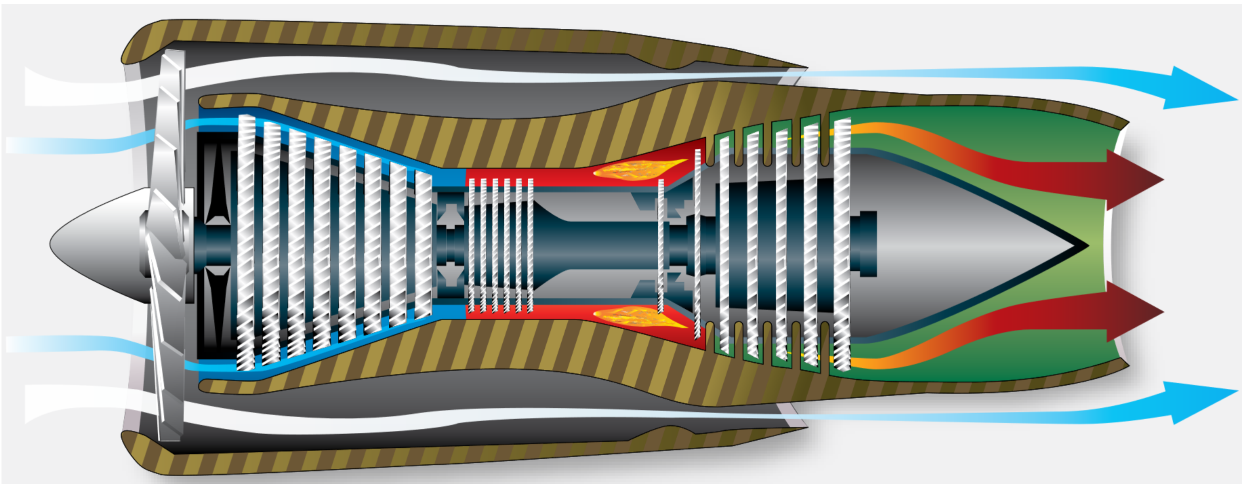

Figure 2: Turbofan Engine Cross Section

Gas turbine engines fall into four categories: turbofan, turboprop, and turboshaft, and turbojet. Turbojets make use of a propelling nozzle to create thrust by allowing the heated exhaust created by a gas turbine to expand, without extracting rotational power from the engine. [9] Turbofans make use of a front mounted fan to extract as much as 80 percent of thrust from the engine, significantly more than their turbojet counterparts. The inlets of turbofans differ from other topologies by virtue of their inlet design, as can be visualized in figure 2. The air driven by the fan will generally bypass the core, the amount of which contributes to the engine's bypass ratio. This ratio is simply the amount of flow through the engine bypass ducts over the flow through its core. The turboprop engine, that which is employed in this paper, drives a propeller through a reduction gearbox. Turboshaft style engines are most often used in helicopters, and are characterized by their transfer of power to a shaft which later connects to another implement such as a propeller transmission or auxilary power unit. [4]

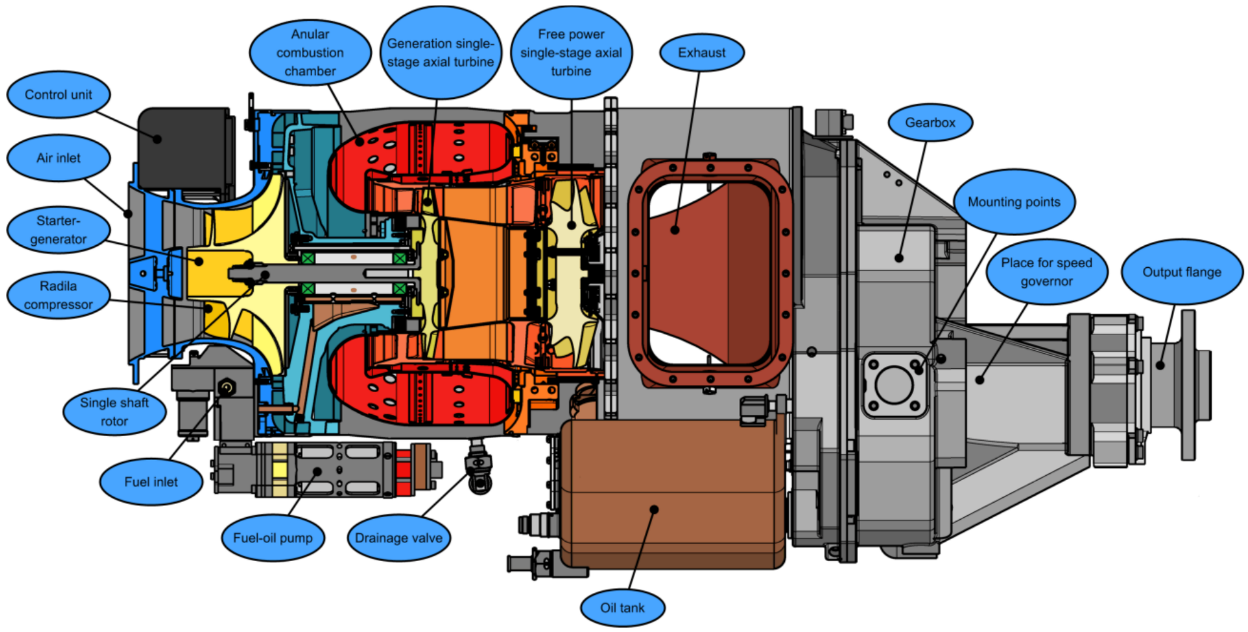

Figure 3: PBS TP100 Cutaway

2.2 Generator Theory

2.3 Battery Theory

2.4 Turboelectric Theory

NASA defines turboelectric systems as being at the least a turboshaft coupled to an electric generator, which power electric motors which then drive propellers. This configuration can be further categorized in accordance with whether the turbine engine drives a load directly. These systems, refered to as "Partial Turbo Electric" [5], employ the use of either turbofans or turboprops in addition to being coupled to electric generators. The last manner in which turboelectric systems can be categorized is with respect to their inclusion of additional power sources. For example, just as is illustrated in figure 5, systems with battery supplementation are called "parallel," whereas those which source power exclusively from their turbine engine are "seires." [5] Both systems constructed for this research are partial by virtue of their

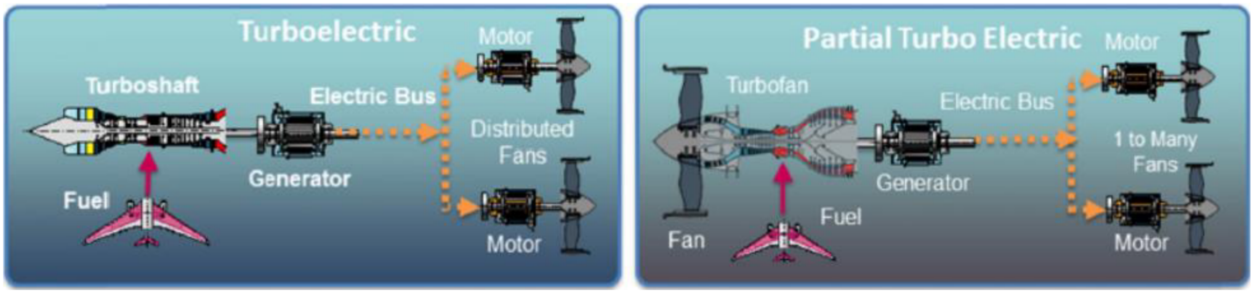

Figure 4: Turboelectric Architectures

turboprop engines. However, configuration 1 is parallel due to its inclusion of a battery, whereas configuration 2 is devoid of additional power sources and is thus series.

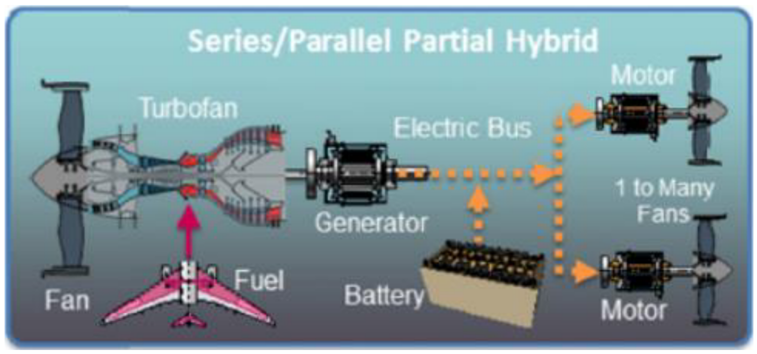

Figure 5: Parallel Turboelectric Design

2.5 Previous Work

CHAPTER III

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3.2.1 Data Acquisition

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3.3 Configuration Two

3.3.1 Data Acquisition

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CONCLUSION, RECOMMENDATIONS, AND FUTURE WORK

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APPENDICES

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VITA

Joshua Drake

Candidate for the Degree of

Master of Science

Thesis: EXPERIMENTAL EVALUATION OF TRANSIENT AND STEADY-STATE CHARACTERISTICS OF A 180KW TURBOELECTRIC-AIRCRAFT TESTRIG

Major Field: Electrical Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Electrical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2024.

Completed the requirements for the Bachelor of Science in Electrical Engineering at Oklahoma State University, Stillwater, Oklahoma in 2020.

Experience:

Research and Design Engineer The Toro Company 2020-2023
Research and Design Engineer OAIRE Current