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Understanding and Controlling Hybrid Electric Gas Turbine Engine Transient Dynamics

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Summary

The electrification of the gas turbine engine is known to increase the flexibility of aircraft architectures by enabling the generation of electrical power to distribute to other electrically based, thrust-producing subsystems. It also has potential for direct performance benefits in the gas turbine engine itself, both at steady state and dynamically. Although the design focus of the gas turbine engine performance is primarily at steady state, it is often the instabilities occurring during transients that cause disequilibrium and constrain performance improvements. Instabilities arise from the disequilibrium of the energy storage mechanisms within the traditional engine system and likewise, for the electrified engine system. The primary energy storage mechanisms in the traditional system are the rotational inertia, gas path volumes, and the thermal masses that make up the mechanical structure; and now, the electrical power system will provide additional contributions. Understanding the effect that each of these energy storage mechanisms has on the others and controlling them appropriately allows for the suppression of state changes within the turbomachinery components to the degree that the components remain near steady state, thus reducing the disequilibrium within the system. The ability to tightly regulate the state changes of turbomachinery components, such as the compressor, minimizes the excursion of the compressor operating point from the operating line (operability), which allows for higher performing, more efficient compressor designs by decreasing the amount of stall margin needed for safe engine power level changes. Preliminary studies with the electrification of the turbine engine have shown that this is possible, and this concept can lead to design trades benefitting engine performance, weight, and volume. This report explores in detail the energy storage mechanisms and control approaches for coordinating their state changes and ultimately proposes that a higher performing, more efficient compressor design can result.

Nomenclature

Acronyms

AGTF30	Advanced Geared Turbofan 30,000-lbf thrust
ASMICS	adaptive sliding mode impedance control with scaling (software)
DC	direct current
HIL	hardware in the loop
HPC	high-pressure compressor
HPS	high-pressure spool
HPT	high-pressure turbine
HyPER	Hybrid Propulsion Emulation Rig
LPC	low-pressure compressor
LPS	low-pressure spool
LPT	low-pressure turbine
NEAT	NASA Electric Aircraft Testbed
OID	operability-influenced design
OTAC	object-oriented turbomachinery analysis code
SAF	sustainable aviation fuels
SM	stall margin
STARC-ABL	Single-aisle Turboelectric AiRCraft with an aft boundary layer propulsor
T-MATS	Toolbox for the Modeling and Analysis of Thermodynamic Systems
TEEM	Turbine Electrified Energy Management

Symbols

α_n	angle between the absolute flow vector and the axial line of the compressor
β_n	angle between the relative flow vector and the axial line of the compressor
$\mathbf{c}_n$	absolute flow vector
n	location within compressor stage
P_t	total pressure, psia
s	specific entropy, J/(kg-K)
T_t	total temperature, °R
$\mathbf{U}$	mechanical rotor tangential velocity vector
W_c	corrected mass flow rate, lbm/s
$\mathbf{w}_n$	relative flow vector with respect to stage location

1.0 Introduction

Aircraft propulsion technologies are increasingly focused on the elimination of all carbon and nitrogen oxide emissions while reducing noise and operating costs (Refs. 1 and 2). In the long term, this may be accomplished using hydrogen fuel or developing an all-electric powertrain, two technologies that have intractable technical, logistical, and infrastructure hurdles to overcome. Alternative fuels such as sustainable aviation fuels (SAF) or ammonia are being considered as nearer term opportunities, still with their own significant roadblocks. In all cases, there is no simple, clear path forward (Ref. 3). This reality is driving near-term innovation into the hybridization of highly reliable turbomachinery-based systems with emerging technologies typically involving electrification (Refs. 4, 5, and 6). Electrification in this context implies that a substantial portion of the gas turbine engine mechanical power is being converted to, or augmented by, electric power for propulsive purposes (Refs. 7 and 8). Most of these concepts involve electric boost or power extraction. Boost employs the use of an electric machine to directly add shaft power to augment the thrust production of the engine during critical phases like takeoff and climb. This enables the turbomachinery to be sized for the cruise condition, thus reducing weight and minimizing fuel burn. Power extraction, however, is a more common area of research. In this configuration, large amounts of power are extracted from the mechanical shaft(s) of the engine, converted to electric power, and typically used to drive electric propulsors on the airframe (Refs. 9 and 10).

Electrification has resulted in a dramatic expansion of the possible airframe architectures for most classes of air vehicles (Ref. 11). For commercial transport-class aircraft, these architectures are aimed at achieving potential improvements in propulsive efficiency by increasing the effective fan bypass ratio through the operation of several smaller electric fans. The use of distributed fans can reduce drag, and the designs often employ boundary layer ingestion for additional propulsive benefit (Ref. 12).

Initially, electrification was not focused on the direct benefit of the gas turbine engine; however, it has created several interesting operational system benefits, such as the elimination of stall margin (SM) overshoot during power level changes and bleedless operation at low engine speeds. All these advantages are being evaluated as trades with implications for system weight and complexity (Refs. 13 and 14). The weight disadvantage of electrification is readily apparent and is a major obstacle to achieving a net benefit for a given system. An electric subsystem for propulsion consists of electric machines and electrical power converters and controllers, an electrical distribution bus, and typically includes a gearbox to match the electric machine performance characteristics to the turbine engine. In more complex architectures, a separate electrical energy storage element is also used. With an increase in the number of required propulsion system components, there is an increase in weight. These weight concerns have spawned a tremendous amount of research to minimize the weight disadvantage of these new powertrain components in achieving feasible flight configurations (Refs. 15 and 16).

The complexity of electrified propulsion is exemplified by the integration of multiple subsystems that are coupled together and affect each other's state. This introduces additional opportunities for unanticipated system interactions that can propagate faults or introduce new system instabilities. Spakovszky (Ref. 17) points out that it is instabilities induced by improperly coordinated changes in the engine state that are the leading cause of program delays and increased costs jeopardizing gas turbine engine certification. These conditions can occur over widely varying time scales that include energy conversion processes among power streams involving the engine gas path, mechanical, thermal, and electrical systems. Simon (Ref. 18) explores the increased complexity and potential for dynamic interactions when these electrified systems are integrated at the vehicle level. Until now, the goal has been to identify and manage these potential instabilities in the interest of improving operability, and thus, safety.

The reduction of instabilities is only partially addressed by simplifying the architectural design of the hybrid propulsion system. Actively coordinating the system state changes via control systems has become a necessity, as the pilot workload to manage the operation of the multidomain system becomes intractable. For that reason, control systems must be considered during the design of such systems. The purpose of this report is to suggest that turbomachinery designers should embrace and leverage the ability of the control system to tightly manage the system state changes. This concept can lead to higher performing compressor designs by minimizing the need for reserving an excessive SM to ensure safe power level changes.

This paradigm change requires a multidisciplinary understanding of the cause and mitigation of these transient dynamics. The aim of this investigation is to systematically address the concepts that chronicle our journey with electrification by connecting the large body of previous work in ensuring system stability to the greater goal of impacting system performance.

The report is organized as follows. First is a description of operability and transient off-design performance. This leads to an overview of energy management control, its implementation, feasibility, and methods of using fuel and electric power to directly control engine shaft mechanical state. Presented next are advances in modeling transient dynamics, followed by proposed operability-influenced compressor design methods. Finally, the report presents the conclusions and potential future research directions.

2.0 Operability and Transient Off-Design Performance

Turbomachinery is tested in a facility under repeatable steady-state conditions to determine its optimal performance characteristics. In normal flight operation, the engine is continually migrating between operating points, during which its transient off-design behavior is exhibited. Transient off design is described as momentary excursions away from engine component operating lines as shown in Figure 1. In extreme cases this can lead to engine instability, damage, and failure. Transient response is generally the performance-limiting factor in operability for the high-pressure compressor.

Transient behavior is dynamical and is associated with various forms of energy being stored within the engine components. In effect, every point on the operating line is a temporary state of equilibrium such that the system must undergo an energy rebalance to adjust to a different point within its operating envelope. Any input, whether from the pilot, the system, or the environment will perturb the operating state of the turbomachinery. Transient operation persists until the energy balance is reestablished at the new operating point.

The engine itself stores a considerable amount of energy using three prominent mechanisms that affect operational thrust production: gas path volume, rotational inertia, and thermal mass. Kerrebrock (Ref. 19) discusses energy conversion and exchange from the turbomachinery perspective. These are also described from an engine control perspective by Jaw (Ref. 20). First, the engine is a pressure vessel, and the many volumes along the gas path have time-dependent responses to disturbances individually These are the most consequential since fluid instabilities increase component losses and produce blockages radially, circumferentially, and axially through the engine, leading to stall and surge conditions. Second, turbomachinery unavoidably has a substantial rotational inertia that causes the mechanical system (shaft spools) to exhibit a time-dependent response. These are observable as lags in thrust response because energy must be added or removed from the inherent flywheel as a prerequisite for a rotational speed change. The last of these is the time dependencies associated with the thermal masses of the system. These have three prominent detrimental effects: (1) time-dependent energy absorption into the structure, (2) changes in tip clearance that greatly affect component efficiency, and (3) time-dependent energy transfer between the fluid and the solid surfaces that impact aerodynamics and the inlet flow to blade rows (stage matching). All of these effects have widely divergent timescales that produce a complex natural transient response in the engine.

Operating transients occur during throttle accelerations or decelerations. Federal Regulation Title 14 CFR 33.73 (Ref. 21) states that engine power must stably advance from 15% of the rated takeoff power or thrust available to 95% within 5 s

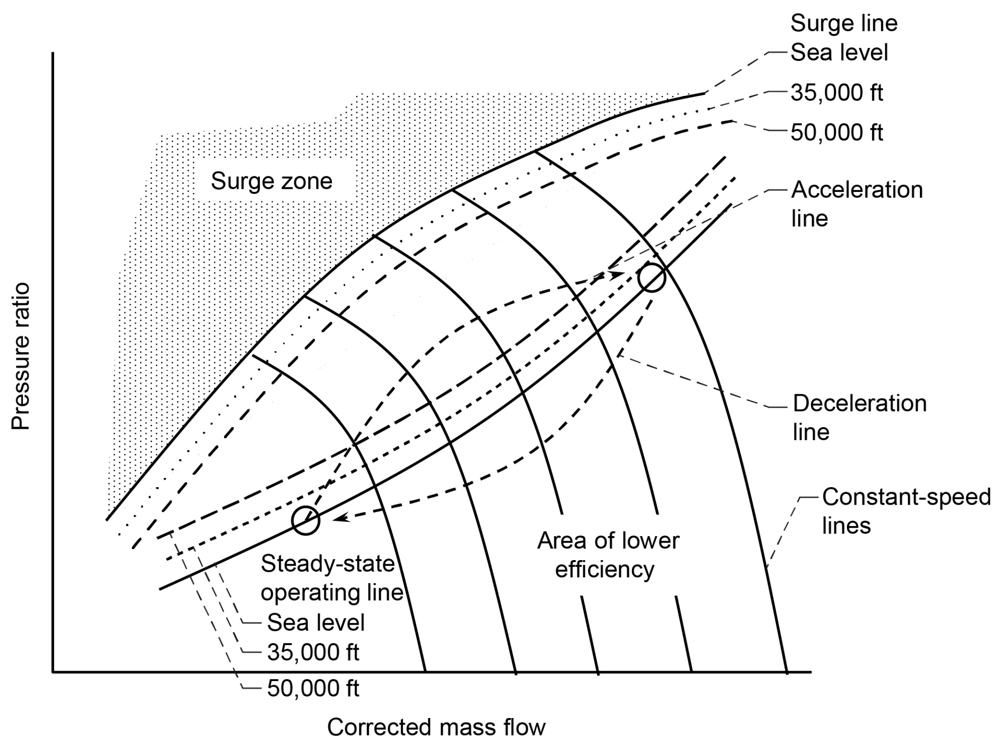

Figure 1.—High-pressure compressor map (Ref. 17) showing the transient off-design operation that needs protection from stall during acceleration.

without overtemperature, overpressure, surge, stall, or other detrimental factors occurring. Deceleration transients, unspecified by regulations, typically last significantly longer, considering that turbomachinery can only produce power to generate thrust and has limited means of decelerating the shaft spools. The fundamental task for control has been to ensure that the off-design transients do not exceed the conditions that guarantee stall-free operation; that is, remaining within the transient stack margin while meeting the engine acceleration requirements.

Closed-loop control in turbomachinery has traditionally been implemented by varying fuel flow along with scheduled (open-loop) actuation of compressor variable geometry and operability bleeds. To avoid all adverse events when throttling engine power, various scheduled maximum and minimum limits on measured engine properties are employed in the controller that constrain the fuel flow rate of change.

Variable geometry is designed to optimize stage matching when the compressor is not operating at its single design point, which is generally the cruise condition. Typically, this actuation scheme is applied to a few of the weakest blade rows in the compressors that limit its performance. Compressor airflow bleeding is another actuation technique that increases inlet mass flow through the compressor during low power conditions for the purpose of reducing compressor blade and stage aerodynamic loading. The bleed flow is generally transferred into the bypass flow and results in a loss of compressor efficiency. These actuation schedules are set during the engine design phase to ensure the compressor operating line holds sufficient SM for operability. SM is a convenient proxy for compressor stability, which is an unmeasurable engine condition. On a compressor map (refer to Fig. 1) there are two common definitions: the distance from the current operating point to the stall line at (1) constant mass flow or (2) at constant rotational speed. Problematically, the stall line position changes with engine degradation and under certain operating conditions.

It is important to understand the physical meaning of SM rather than fixating on its probabilistic value determined from a compressor map. The root physical cause of compressor instability and stall is flow blockage in the compressor gas path. In the compressor, the rotor blades convert kinetic energy to thermal energy within the flow, which both the rotor and stator vanes diffuse and convert to potential energy, slowing the velocity and creating a rise in pressure. Turbomachinery designers use the concept of velocity triangles (Ref. 22), shown in Figure 2, to optimize the energy exchange between the mechanical and fluid systems in the compressors and turbines. The vector **U** describes the mechanical rotor tangential velocity; and $\mathbf{c}_n$, $\mathbf{w}_n$, β_n, and α_n describe the absolute flow vector, relative flow vector, the angle between the relative flow vector and the axial line of the compressor, and the angle between the absolute flow vector and axial line of the compressor. The subscript n denotes locations upstream of the rotor (1), rotor exit (2), and stator exit (3). Subtracting **U** from $\mathbf{c}_1$ yields the relative velocity $\mathbf{w}_1$ and its angle β_1 with respect to the rotor blade. Adding **U** to $\mathbf{w}_2$ yields the absolute flow velocity $\mathbf{c}_2$ into the stator at angle α_2. The red vectors indicate reduced flow relative to blade velocity and how the flow propagates downstream, affecting compressor performance. The velocity triangles illustrate this direct relationship between the mechanical inertial and gas path

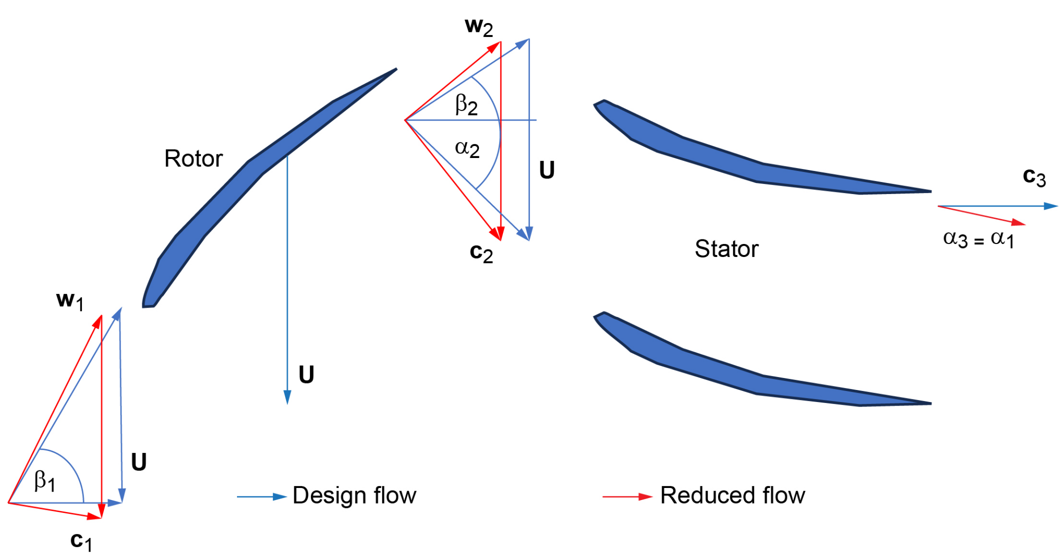

Figure 2.—Turbomachinery velocity diagram illustrating relationship between rotating wheel speed (**U**) and the gas path velocity and incidence angle into airfoils (rotor: $\mathbf{w}_1$, β_1) and (stator: $\mathbf{c}_2$, α_2).

volume time dependencies, two of the fundamental energy storage mechanisms in turbomachinery. When operating the engine transiently, the relative change in the two vectors occurs at different rates, violating the steady-state relationship and altering the flow incidence angle onto the airfoils. This excites entropy production and flow blockage, producing a transient flow mismatch for the following stages.

Consider Figure 3, while referring to the compressor map in Figure 1, to appreciate the complex dynamics that are initiated during acceleration by adding fuel to the combustor. As fuel is added, the flow exiting the combustor has increased enthalpy with a small increase in mass flow. The flow entering the combustor, however, will not change appreciably until the high-pressure turbine (HPT) begins extracting work from its entering flow and thereby power the high-pressure compressor (HPC), to which it is connected by a mechanical shaft. A similar scenario unfolds with the low-pressure spool (LPS), further delaying the recursively changing conditions in the high-pressure spool (HPS). As the HPC begins to accelerate, the HPC inlet pressure is reduced because of the delayed supply of air from the low-pressure compressor (LPC). This phenomenon increases the HPC pressure ratio and causes the HPC to operate with a deficient inlet mass flow. The result is a significantly reduced HPC SM. In contrast, the LPC experiences increased SM because its pressure rise is restricted by an increased demand in mass flow from the HPC, even while the LPC mass flow begins to increase.

A somewhat reverse situation develops on deceleration, when the energy held in the rotating mass of the LPS serves to continue to drive the LPC flow into the HPC, even while the combustor fuel is being throttled down. In this situation, the LPC pressure ratio increases while the lower inertia, HPS speed slows, pumping less fluid and restricting the mass flow in the gas path, which results in a reduced LPC SM. This increases inlet pressure to the HPC while the HPC is attempting to decelerate its pressure ratio increase. The result is an increase in HPC SM and the possibility of very lean fuel-air ratio conditions in the combustor, threatening blow out.

It is the close coupling of mechanical and fluidic time-dependent changes, and the indirect control of the turbomachinery shaft speeds via the fuel flow rate, that has made compressor stability the limiting factor in turbomachinery performance. Up to half of the SM reserved in the compressor design is devoted to transient operations (Ref. 17). Electrification now provides the means for the direct, independent control of mechanical shaft time-dependent behavior. The coordination of the inertial and volumetric energy storage mechanisms during operation can result in turbomachinery operation that approximates a steady-state condition, thus reducing the disequilibrium, or entropy production, in the gas path.

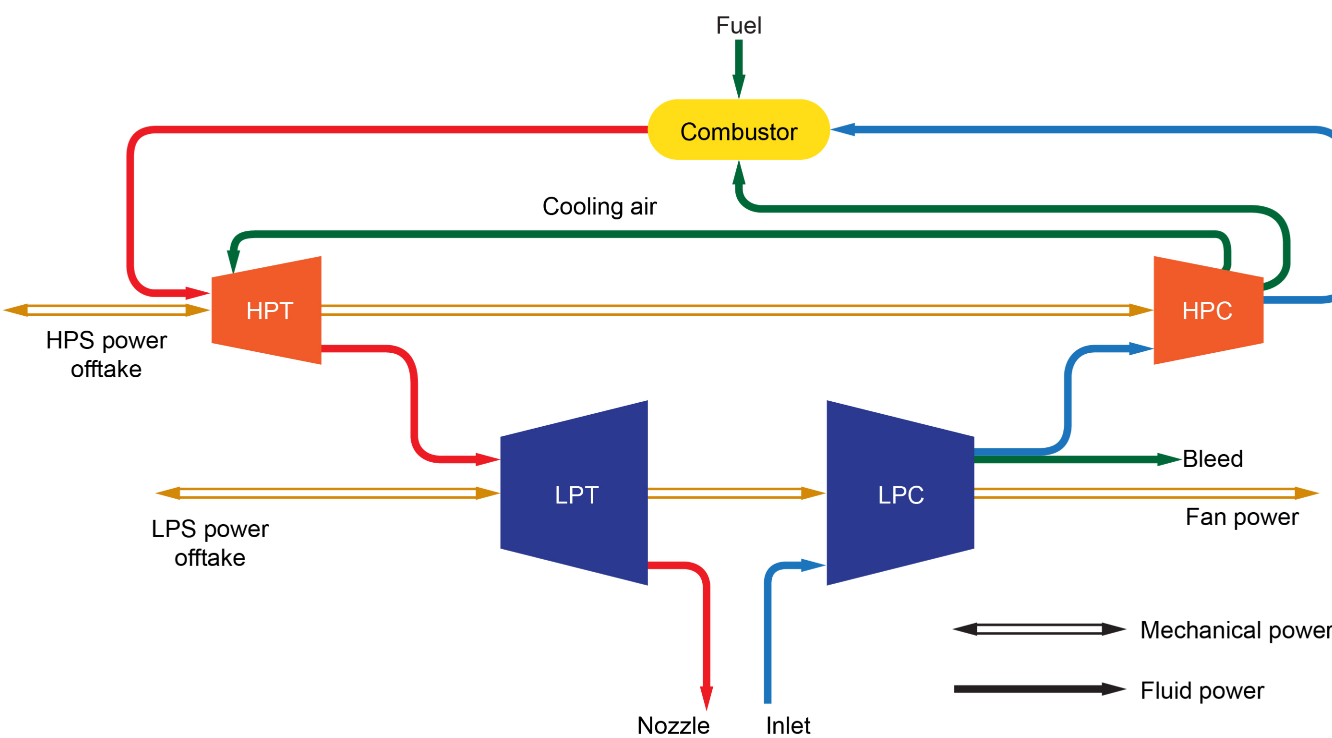

Figure 3.—Illustration showing energy pathways between gas turbine engine components. Red and blue lines indicate hot and cold air, respectively; green lines indicate airflow transferred via bleeds; and gold lines indicate mechanical coupling. LPT is low-pressure turbine.

3.0 Energy Management Control

Electrification of the gas turbine engine was first proposed to counteract the diminishing returns of increasing fan diameter on propulsive efficiency (Ref. 23) by achieving a higher effecttive bypass ratio with multiple smaller electric fans. Various concepts were explored under the umbrella term of “more distributed propulsion.” However, coupling turbomachinery with electric machines introduces electrical dynamics that change several orders of magnitude faster than the turbomachinery thrust response. Coordinating these additional dynamics with the rest of the mechanical and thermodynamic system is necessary to ensure engine stability. It was these concerns about the impact on engine stability that evolved into a control philosophy designated by the NASA as “Turbine Electrified Energy Management (TEEM)” (Ref. 13), which leverages the electric machines for use as stability control actuators.

Initial simulation studies were focused on control methods for the protection of SM, where transient conditions caused the rotational velocity of the blading on both spools to be delayed with respect to the gas path velocity (see Fig. 2). The first assumption was that to counteract the loss of SM, both spools required power injection when accelerating and power extraction when decelerating to maintain the appropriate relationship between spool speeds and airflow. This was soon proven to be unnecessary, as the loss of SM is isolated to the HPS when accelerating and the LPS when decelerating. Studies by Kratz (Refs. 24 and 25) using the conceptual Advanced Geared Turbofan 30,000-lbf thrust (AGTF30) engine model (Ref. 26) demonstrated that this simplification created turbomachinery operability benefits throughout the flight envelope. The AGTF30 is a MATLAB®-Simulink® (The MathWorks, Inc.) implementation of the NASA reference propulsion system (Ref. 27). It uses a numerical energy balance method at the component level and performance maps to define the nonlinear turbomachinery system. Simultaneously, the Single-aisle Turboelectric AiRCraft with an aft boundary layer propulsor (STARC-ABL), a NASA-designed conceptual electrified aircraft, was studied and shown to benefit from the addition of electrical energy storage and TEEM control as well (Ref. 28).

These early efforts were followed by higher fidelity simulations and hardware-in-the-loop (HIL) experimental studies to demonstrate the feasibility of using the electrical power system to mitigate compressor stall under large power extraction conditions, generally looking at two-spool power extraction configurations on turbofan engines. What follows is a discussion of these studies for implementation and feasibility of energy management control progressing toward a capability to impact gas turbine engine performance.

3.1 Implementation and Feasibility

The simplification of TEEM allowed for the bifurcation of the control approach addressing accelerations and decelerations. In the early simulations, there was no electrical system model. Power was simply inserted via a power offtake variable in the model of the HPS during acceleration to reduce the aerodynamic loading in the HPC. During decelerations, power was extracted from the LPS to reduce the aerodynamic loading in the LPC. Both techniques demonstrated that the off-design operation of the loaded compressor could be reduced or even forced back to the operating line, or beyond, based on the amount of power used.

To increase the practicality of the simulations, improvements were incorporated to accurately model the electrical systems. TEEM needed to leverage the electric machines in the existing design of the propulsion system as fast, high-control-authority actuators for turbomachinery transient control in addition to their primary role as power conversion devices. Consideration of how this would work within the existing framework of the concept vehicle was important. This dual-use technique required that a machine could be rapidly switched between motoring and generating modes of operation by its controller, while always operating in a single rotational direction. It also took advantage of an electrical energy storage device that could be used as an independent source of energy for operability control during transients. The general configuration is shown in Figure 4.

The independent energy source allowed for the momentary decoupling of the electric loads from the turbine-engine-driven generator; the main task of the generator is to power those electric loads. Energy from the energy storage device would supply power to the downstream loads while simultaneously

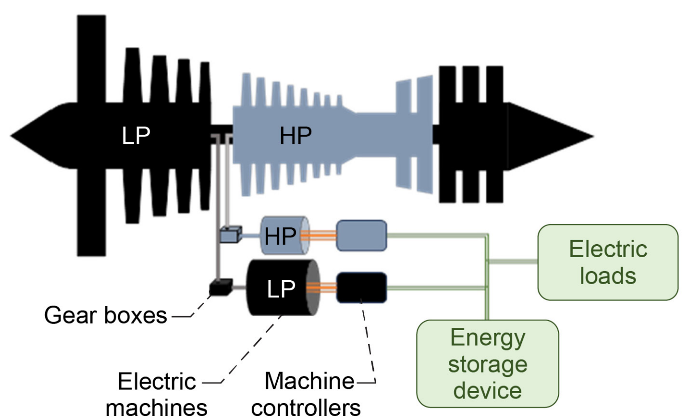

Figure 4.—Electrified turbofan engine with two-spool power extraction, a coupled energy storage device, and electrical loads.

either sourcing power to the high spool or absorbing power from the low spool: the former would occur during an acceleration, and the latter, during deceleration. Additional refinements to this approach are discussed in Section 3.2, “Torque Shaping and Optimization.” The energy storage device also employed a DC-DC converter in front of the battery for three purposes: (1) to boost battery voltage, (2) to regulate the DC bus voltage in the interest of providing consistent motor performance, and (3) to allow for the energy storage device to maintain a static state of charge. The energy storage element could be a battery, but it was generally considered to be more practical to use a supercapacitor to avoid the charge and discharge limitations of batteries. These practicalities forced several constraints on the system; specifically, electric machine power and energy storage capacity, which essentially is a weight, volume, and performance trade. Ideally, the transient control could be accomplished by the baseline electrified propulsion architecture and not drive the sizing of the electrical design. There are several studies that examine these complex trades (Refs. 29, 30, 31, 32, and 33).

As the technology matured, the issue of feasibility in using the electric power system for stability control in a hybrid propulsion architecture needed to be demonstrated. This involved experimental efforts in two facilities. The first was in the NASA Electric Aircraft Testbed (NEAT), using megawatt-scale electric machines. The second was in the newly constructed Hybrid Propulsion Emulation Rig (HyPER), using 60-kW machines. Both HIL facilities utilized an experimental electric power system driven by the emulated shaft interfaces of a two-spool turbofan engine using electric machines driven in torque mode. Typically, the engine model was the AGTF30, with the TEEM controller providing closed-loop control. In all cases, the engine simulation and controller were operated at full scale while the HIL torque and speed outputs were scaled for the specific test facility hardware, while preserving the full-scale turbomachinery shaft time dependencies. This capability was provided by an adaptive sliding mode impedance control with scaling (ASMICS) software (Ref. 34). The details of NEAT and HyPER test facilities are covered in several publications (Refs. 35, 36, and 37). The results of these experimental investigations demonstrated the immense capability of the electrical power system to perform transiently for the benefit of turbomachinery stability control (Refs. 38 and 39).

3.2 Torque Shaping and Optimization

The application of torque via the electric machines for control of the gas turbine engine has evolved considerably. The attempts at optimizing the application of electric machine torque throughout a propulsion system transient will be referred to in this report as “torque shaping.” The following efforts have demonstrated electric machines can respond with sufficient speed and authority to maintain compressor stability. The machines also can easily react to throttle demands and to asynchronous variations in the loads supplied by the engine. In Reference 40, Kratz develops optimized fuel flow schedules using genetic algorithms. Kratz (Ref. 41) then sequentially applies genetic algorithms to develop controllers for implementing TEEM control in coordination with optimized fuel schedules. In previous efforts, the use of electric power had been commanded through an inner closed-loop correction to the basic outer closed-loop fuel flow rate controller. Using the optimization technique, a reduction in the use of electric machine power was realized along with a further simplification of the electric control via use of a scheduled approach. The transient response benefit was quantified in terms of transient stack usage and transient excursion integral. The former is a measure of the maximum penetration into the transient stack at any point, and the latter is a measure of the overall usage of the transient stack area to perform the control. The result is shown in Figure 5, illustrating the increase in the distance between the operating point and the stall line during an idle-max-idle throttle movement when TEEM is implemented as opposed to without TEEM.

In a related study, Litt (Ref. 42) further expands the previous approach by applying genetic algorithms to simultaneously optimize both the fuel flow rate and electric power. The AGTF30 engine model was also modified for the first time to incorporate the effects of heat soak and HPT tip clearance control. Although the engine control was still effective at suppressing compressor transient off-design operation, the impact of thermal dynamics significantly changed the results.

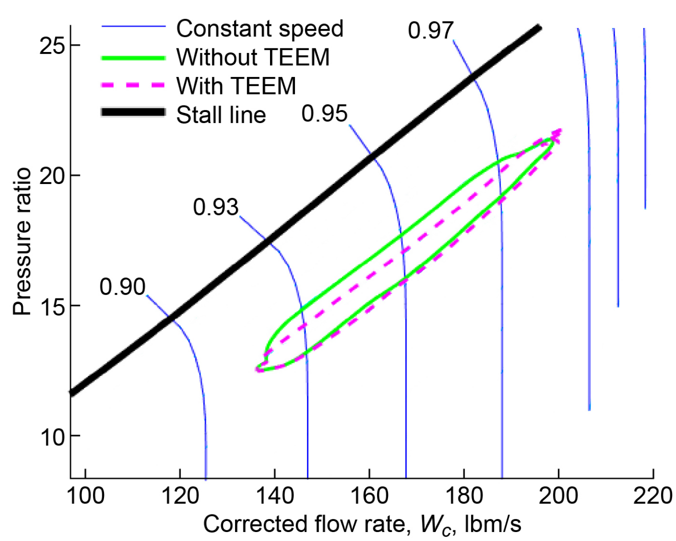

Figure 5.—Replotted results from Kratz (Ref. 41) showing the operating point trajectories during an idle-max-idle throttle maneuver with and without TEEM.

This study did not investigate deceleration or other concerns with thermal time-dependent responses such as Bode maneuvers (repeated accelerations and decelerations) and aerodynamic effects.

The most recent efforts at torque shaping indicate that electric machine torque could be tailored together with the fuel flow rate profile to address specific portions of the transient timeline. This suggests that the objectives for the transient control can change, even within a specific transient event. For example, SM protection may be traded for minimizing peak temperature (Ref. 43) or maintaining component efficiency.

The fundamental approach to controlling transient time-dependent responses is becoming clearly understood and is important for stabilizing electrified propulsion architectures. However, the benefits of the technology have been primarily applied for operability, an important safety issue, but have not yet been shown to provide an engine performance benefit. Still, the potential for operability to be used specifically for engine performance enhancement was recognized, and more attention has been focused in that area. For example, Jing (Ref. 44) recently considered using similar technology to enhance acceleration in low-bypass turbofan engines.

One immediate engine performance benefit that has been observed evolved from the low spool method of transient control during decelerations. Because of the low spool's large inertia relative to that of the high spool, significant amounts of power can be extracted, driving the sizing capacity of the electrical energy storage device. Under extended-duration low-engine-power settings typical of the mission segments of approach and landing or ground operations, there is also minimal LPC SM, and more significantly, poor engine efficiency. Here, a bleed is often used to increase the mass flow through the LPC to push the operating point further from the stall line. The fluid extracted from the compressor is transferred into the bypass flow, resulting in a loss in power and efficiency. This power loss can be eliminated by replacing the bleed with an electric machine functioning as a generator, transferring the power through the electrical system to the HPC. The result is higher efficiency operation and reduced fuel burn for the engine. This requires the electrification of both spools. For extended periods of low-power operation, the benefit increases engine efficiency, producing about a 10% fuel burn reduction for those mission segments. This is especially impactful for short-duration flights (Ref. 14).

A second engine performance benefit requires a paradigm shift in design philosophy: one that embraces controls to achieve a step change in engine performance. This philosophy broadly applies the transient control techniques described earlier to justify a large reduction in the high-pressure compressor transient stack margin to near zero. Roughly half of the total compressor SM is devoted to transient operations (Ref. 17). The successful demonstration of a controls-based operability improvement can lead to turbomachinery designers being able to recover this large area of the compressor map, used only for transient off-design operation, for performance gains. Even though this could help increase the HPC pressure ratio, the difficulties with decreasing the dimensions of the last blade row would likely favor pursuing weight and volume reductions instead of performance increases. The most likely impact of a minimal transient stack would be reduction in the number of stages and solidity (ratio of the aerodynamic chord over the peripheral distance between two adjacent blades) as the pressure rise is redistributed across the LPC and HPC with reduced blade losses (higher efficiency). Depending on system details and objectives, this could represent several percentage points in fuel burn reduction over the entire mission.

4.0 Transient Modeling and Dynamics

Although it is encouraging that torque shaping holds promise to address specific control actions that can potentially mitigate the performance-limiting transient response, the factor limiting the use of energy management control is our physical understanding of the transient itself. The physical understanding of gas turbine engine transient behavior is hindered by access to empirical data. As previously mentioned, most engine component tests are intended to define performance under steady-state conditions. Also, obtaining high-frequency measurements of the gas path is extremely difficult because of the lack of access, measurement techniques, facility capabilities, and especially the expense. Even though understanding transients at the component level is important, the overall system transient response is determined by each component's effect on the others. For these reasons, modeling is the most appropriate activity for developing an improved physics-based understanding of the transient phenomena. This is likely to have the added advantage of being related to component geometry. Thus, the time-dependent responses of the components and system should be considered during the design phase of the component and system.

Perturbing the gas-path state must be avoided to guarantee the stable, stall-free operation of the gas turbine engine. However, it is interesting to consider what is happening with the mechanism that is exciting the gas-path state in this situation. Cumpsty (Ref. 45) considers compressor stall and surge in some detail, although as a flow disturbance not caused by the fundamental operation of the engine. If a throttle movement can be considered a flow disturbance into a fixed spool speed, then it would likely be modeled as a full circumferential, large disturbance to the compressor, producing the most severe effects. In our control methodology, we are attempting to change the spool speed to minimize the magnitude of this disturbance to the flow.

Considering the idea of the transient as an energy imbalance, we then should be able to model the power flow through the engine system along with time-varying changes in the stored energy in the gas turbine components. Effectiveness of the control should appear as an ability to minimize the stored energy deviation in the turbomachinery components from their steady-state values. The expectation for the overall transient is described in a simple manner in Figure 6, as a timeline of energy disequilibrium recursively spiraling out from its origin in the combustor to the LPC. Still, validation of the model is difficult except at the start and end points of the overall transient where the steady-state and transient models must match by definition.

This approach is currently being modeled using NASA's Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) (Ref. 46). Here, the Volume block is modified to incorporate the instantaneous, time-varying, fluidic energy storage as signified by changes in enthalpy and the mass flow differential across each component block that persists only for the duration of the transient. This was incorporated into the AGTF30 model to get a better estimate of the transient control effectiveness relative to the perturbation of the gas-path state (Ref. 47).

Next steps would be to incorporate thermal, time-dependent state variables that model the phenomena of heat soak, turbine tip clearance, and aerothermodynamic flow effects that alter the engine performance as described in Reference 42. Gas path flow is the source of both heating and cooling effects inside the engine, and it is a reasonable assumption that the use of electric power to alter the mechanical state will moderate peak temperature changes downstream of the combustor during accelerations.

5.0 Operability-Influenced Design

Propulsion system electrification creates an opportunity to improve gas turbine performance by modifying engine dynamic operation, the leading cause of an engine's performance-limiting instabilities. This is enabling for a new compressor design process that utilizes physics-based entropy rise models rather than the empirical pressure loss models that have traditionally been used in the design of new compressors. An overview of the methodology is presented here.

Entropy rise models refer to loss models that track entropy generation within a compressor. Given compression in the Brayton cycle is ideally isentropic, the entropy generation is ideally zero. Thus, any entropy generation relates to inefficiencies in the compression process. Other loss model methods rely on empirical relationships developed with data that are often proprietary and/or specific to a compressor design. Entropy rise models focus on approximating changes in thermodynamic performance based on a variety of factors such as friction, end-wall losses, clearance losses, shock losses, and so forth. This approach retains more physical meaning and is more generic. Entropy rise models can be employed to match the performance of a known design or to alter a design. When combined with a technology such as TEEM, entropy rise models play a role in the redesign of the compressor to take advantage of the ability to reduce stall margin. The loosening of operability requirements opens up the compressor design space. With the reduced need for stall margin, the compressor can be redesigned to achieve lower entropy generation as predicted by the model, which equates to higher efficiency. The design can also be modified to consider other potential benefits such as weight reduction, for which component efficiency and weight will need to be considered simultaneously under the raised operability constraint.

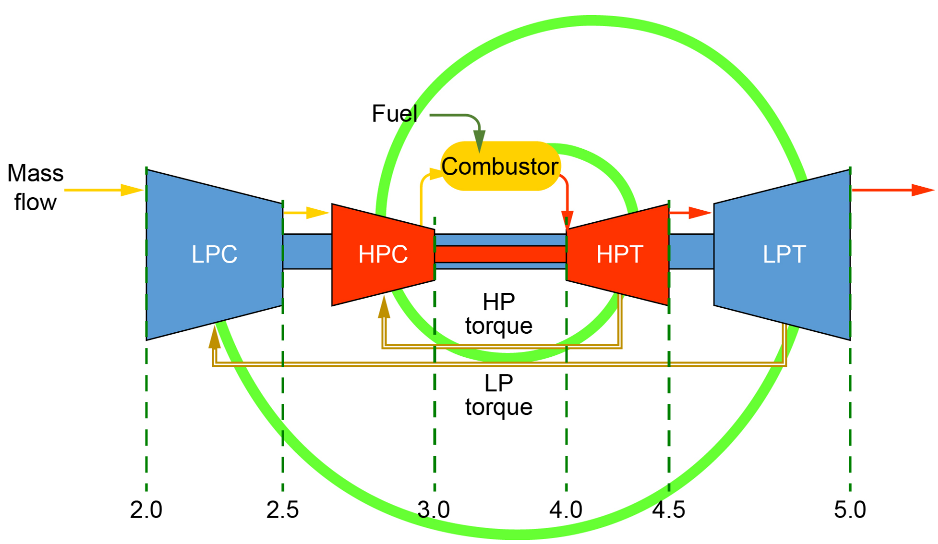

Figure 6.—Gas turbine engine dynamic transient response originating from the combustor and spiraling out over time to other components.

This process leverages NASA's object-oriented turbomachinery analysis code (OTAC) (Refs. 48 and 49), which was modified to account for entropy rise calculations across each compressor blade row. A significant effort was expended to identify various existing entropy rise models and assess their performance when applied to the NASA Energy Efficient Engine (E3) HPC model. These models were mostly guided by Denton's approach (Ref. 50) to identify loss mechanisms in turbomachines. The entropy rise models were then modified or further developed to match the known entropy rise from the extensive E3 HPC database (Refs. 51 and 52). From there, a new steady-state model of the 10-stage HPC was developed. The off-design performance of the new HPC model was also assessed, requiring further adjustment of the entropy rise models to match the E3 HPC database.

A comprehensive literature review was conducted to identify pressure loss and entropy rise models and evaluate their effectiveness in predicting the performance of the E3 HPC. Pressure loss coefficients, being empirical models derived from experimentation, have limited adjustability, mainly confined to blindly altering the model parameters, specifically when applied to more modern designs. Conversely, entropy rise models are developed by simplifying the physics of loss mechanisms. Therefore, enhancing the current entropy rise models by adding complexity to these simplified models, or adjusting the underlying assumptions, can offer a more physically meaningful approach to match the performance of the E3 HPC (Ref. 53). Four primary sources contributing to entropy rise were analyzed: blade profile, end-wall flows, shock, and tip leakage. For each category, at least two models were identified and further refined.

As an example, profile entropy rise predominantly stems from the boundary layer along the suction and pressure surfaces of the blade, which correlates with the velocity distribution across the blade. To address this, simplified—but variable—velocity profiles were examined for rotating and stationary blades individually. This approach allowed for the development of distinct entropy rise models for each type of blade row. One of the challenges with these models is their generality; rooted in simple physics, these models need to be tuned to the proper application, and this process limits their capability.

Figure 7(a) illustrates the estimate of the rise in specific entropy, s, versus the stator and rotor row number calculated from the proposed models (Total Rise Model) and the E3 test data (Total Rise E3). Figure 7(b) shows the calculations of s from the E3 test data versus the stator and rotor row number, comparing the specific entropy (Total Rise E3) test data for each stator and rotor into four contributing phenomena obtained from the model: profile rise, tip leakage rise, shock rise, and endwall rise. The magnitude of estimated entropy rise using the proposed models is generally lower than the E3 amount except in rotors 1, 7, and 9 and in the final stage. Estimating entropy rise in rotor 1 is challenging because of the existence of shock waves and because the model used seems to overestimate entropy rise due to the shock at this stage. One of the compressor bleeds is at stage 7, causing irregularities in the estimation of end-wall losses in rotor 7. It proved to be challenging to estimate the entropy rise at the last stages of the HPC. This is most likely due to the overestimation of the end-wall losses and a shortcoming of the model used here.

The modifications to OTAC were categorized into two main groups. First, enhancements involved incorporating entropy rise calculations into the code, enabling users to input estimates of entropy rise for each blade row either through experimental data or entropy rise models. The code utilizes the user's initial estimate to solve for each blade row and compute flow characteristics at the blade row exit. Additionally, a separate module was created to integrate all entropy rise models considered in this study.

Second, adjustments and further developments were made to OTAC elements to facilitate the proper design of the E3 HPC. This included developing an element to accommodate compressor bleed at stages 5 and 7 as well as introducing a blockage element to incorporate blockage effects in blade row calculations. Also, a new expander element was created to allow users to define compressor input profiles based on Mach number, total pressure, and total temperature distributions.

Figure 8 shows total pressure, P_t, and total temperature, T_t, versus the inlet guide vane, rotor, and stator row number, comparing the E3 test data to the OTAC model with and without the entropy rise method. The plot shows good agreement between the HPC models developed in OTAC and the values from the test data.

The objective of the design is to minimize entropy rise, thereby reducing losses throughout the machine and enhancing the compressor's efficiency. Operability-influenced design (OID) facilitates improvements in compressor design through two primary avenues. First, leveraging electric machines to control the transient performance of the engine and compressor can substantially diminish the SM required, potentially leading to a more compact compressor design. Second, a more aggressive blade design can be integrated to notably decrease entropy rise resulting from blade profile and endwalls. Therefore, redesigning the compressor blades to decrease entropy production near the operating line at the expense of off-design operation theoretically enables increased on-design pressure rise. This, in combination with minimizing excursions from the operating line demonstrates the plausibility of OID. Compressor rotor blade design needs to balance efficiency and sensitivity to the inlet flow angles. With the capability of OID to control stall instances, these blades may be designed with more flow angle sensitivity and higher efficiency. However, these competing goals define a trade space that still needs to be fully explored.

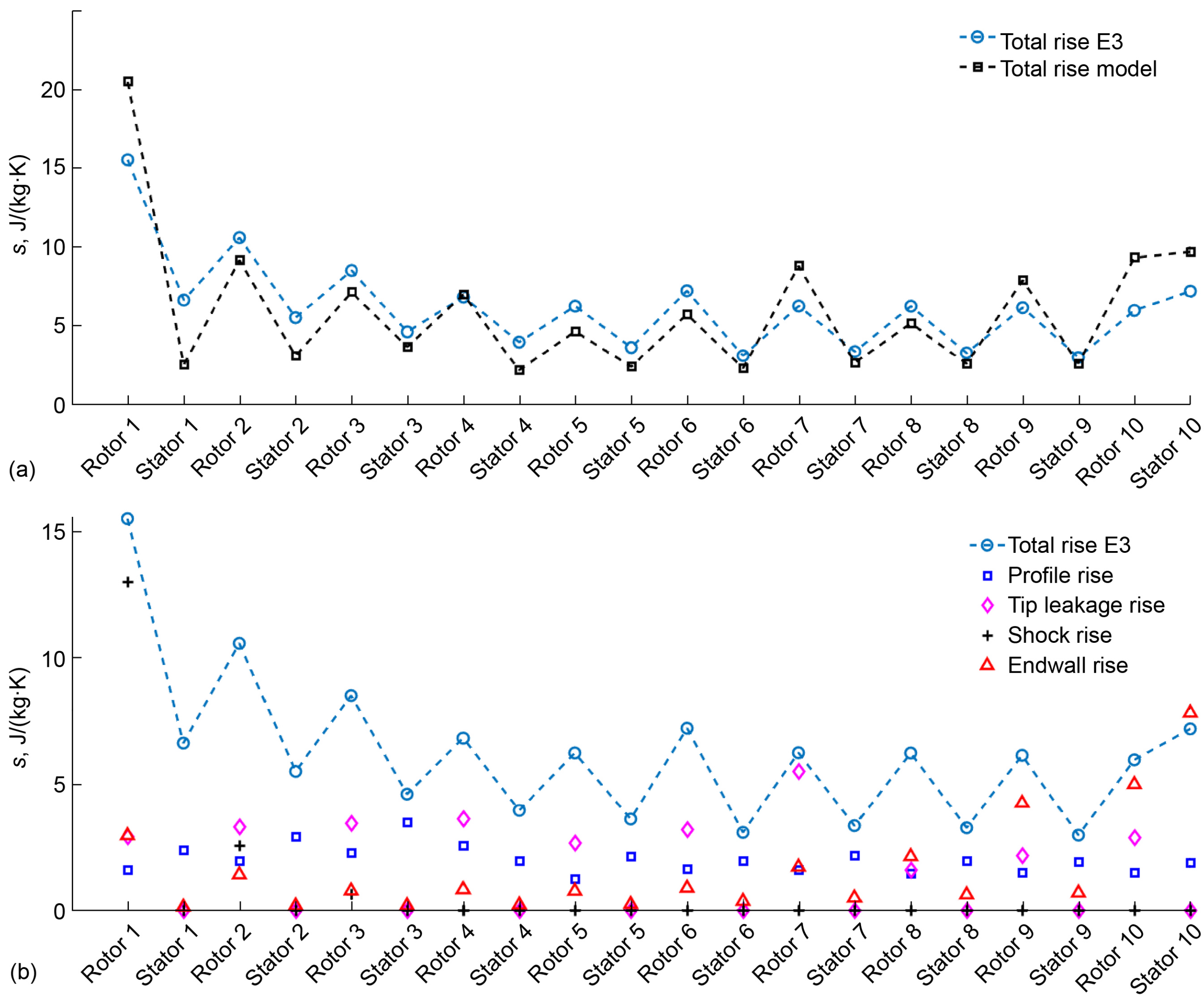

Figure 7.—Specific entropy rise *s* at design point versus rotor and stator blade row number (a) Comparison of entropy rise model and E3 test data. (b) Comparison of E3 test data specific entropy rise and each model component that contributes to the total rise calculation.

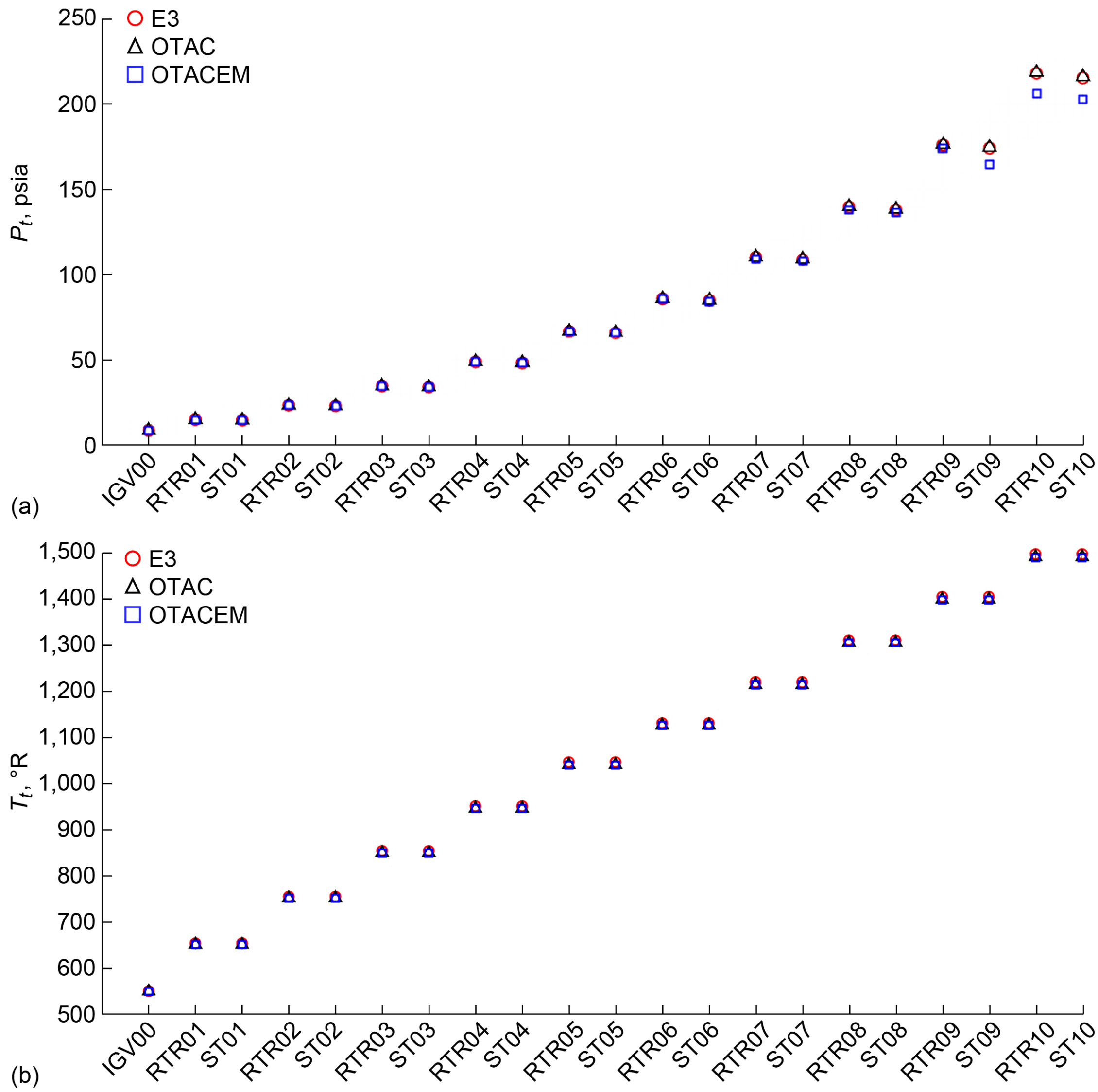

Figure 8.—Total pressure and total temperature versus inlet guide vane (IGV), rotor (RTR), and stator (ST) row number, comparing the E3 test data (E3) and the OTAC model without (OTAC) and with (OTACEM) the entropy rise method. (a) Total pressure, P_t. (b) Total temperature, T_t.

6.0 Conclusions

New aircraft and propulsion systems are leaning heavily into electrified architectures as a pathway for meeting government environmental regulations and the endless quest for lower operating and maintenance costs. Although not ideal in the sense of achieving zero emissions, electrified gas turbine engines are enabling for transformational changes in the flexibility of aircraft design and energy optimization leading to reduced fuel burn.

The move to electrification significantly changes the propulsion system powertrain, adding more components with increased complexity and weight. There has been great progress in reducing the weight and volume of the electrical systems, and this will continue as the long-term presumption is that all-electric powertrains are the ideal. What will also continue is an increase in system complexity and a corresponding concern with potential system-wide instabilities from vehicle-level interactions. This will result in an increasing future reliance on controls. However, propulsion electrification has demonstrated real benefits for compressor stability. Here, electric machines used for power conversion become dual-use actuators for protecting stall margin during transients by using bidirectional power flow to affect compressor blade loading. When this technique is extended beyond transient operation, it becomes a method for power transfer between spools to affect the engine cycle for improved performance. Furthermore, this can all be accomplished using the electric machines within the existing designs; that is, they do not drive the sizing requirements.

The limiting factor on energy management control technology is a more detailed understanding of engine gas path dynamics and how power is converted and flows through multiple pathways in the engine under transient conditions. Research to better understand these phenomena, such as modeling of heat transfer and volume dynamics, can provide insight that enables optimized power injection and/or extraction schedules.

Ultimately energy management technology, used collaboratively with fuel management, has the potential to fully control engine shaft dynamics. This will minimize the off-incidence flow across the gas path blading, eliminating compressor instability. In this capacity, the high-pressure compressor transient stack will be managed to near zero margin, thus enabling designers to achieve a step change in compressor performance through operability-influenced design.

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