

Transient Engine Emulation within a Laboratory Testbed for Aircraft Power Systems

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ABSTRACT

This paper presents the details of an engine emulation system utilized within a Hardware-in-the-Loop (HIL) test environment for aircraft power systems. The paper focuses on the software and hardware interfaces that enable the coupling of the engine model and the generator hardware. In particular, the rotor dynamics model that provides the critical link between the modeled dynamics of the engine and the measured dynamics of the generator is described in detail. Careful consideration for the measured torque is included since the measurement contains inertial effects as well as torsional resonances. In addition, the rotor model is equipped with the ability to apply power and speed scaling between the engine and generator. This scaling approach provides significant flexibility that can be useful when hardware resources are limited such that a direct engine-generator match is not possible or when one wants to evaluate turboshaft engine dynamics for a variety of applications and power levels. Depending on what type of scaling is used, there may be an effect on the maximum power the drive stand must provide to fully emulate engine transients. Explicit torque/power requirements are given, along with an evaluation of the existing drive stand's emulation capabilities.

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INTRODUCTION

The design of electrical power systems (EPS) for more electric aircraft architectures continues to be a challenging problem. The introduction of pulsed loads, such as radar and directed energy weapons (DEW), places a significant demand on the capabilities of the EPS. Pulsed loads are typically characterized by a high peak-to-average power ratio and dynamic on-off pulses that can lead to complicated transient and harmonic interactions. The ability of the turbine engine to handle the pulsed, transient horsepower extraction is of particular interest. Addressing these challenges in an effective manner requires an integrated approach, utilizing both laboratory testing, as well as modeling, simulation, and analysis (MS&A). A representative laboratory testbed has been developed to investigate Integrated Power and Thermal Management System (IPTMS) technologies for high pulsed-power loads. Unfortunately, laboratory testing of the full-scale power system with an actual turbine engine is cost-prohibitive and limited in flexibility. As a result, it is necessary to investigate engine dynamics using real-time models coupled with hardware emulation.

Emulation of gas turbine dynamics has been discussed previously in the literature, with particular interest given to the ability of an emulation system to fully capture the transient engine dynamics. There can be several challenges to successful emulation including the drive stand limitations, the fidelity/validity of the real-time models, and the latencies throughout the system due to communication rates, A/D conversion, filtering, etc. For the engine emulation setup presented in [1], the researchers investigate methods to compensate for significant time delays between the real-time simulation and the hardware system. In [2], a power criterion for selecting emulator hardware is presented and the requirements on the emulator bandwidth are discussed. An aeroderivative twin-shaft gas turbine engine is emulated in [3], and the accuracy of the emulation is considered with differing inertia values for the emulator hardware. Reference [3] also discusses the presence of non-engine related torque dynamics in the measured signal and how they were removed. In [4], the emulation setup for a two-spool, turbofan engine is discussed in detail, and the response of the emulation hardware was shown to be insufficient for capturing the higher frequency engine dynamics.

As with previous research, the engine emulation approach developed herein attempts to assess the emulator capabilities and minimize any possible discrepancies between engine emulation and engine hardware. To accomplish these goals, the rotor model that provides the coupling between the real-time engine simulation and the measured generator dynamics is described in detail to ensure proper implementation. In addition, the laboratory system and available hardware differ somewhat from typical emulation systems in that the power and speed of the selected laboratory generator does not directly align with the turbine engine. Since the lab objectives are more focused on general power system integration than specific aircraft hardware testing, the mismatched speed and power are not a significant detriment; however, the mismatch does need to be handled by the rotor model. As a result, an approach for power and speed scaling is presented that enables engine to generator coupling and also provides flexibility in the emulation setup. Finally, initial testing with the engine emulator is presented, and the ability of the emulator to closely track engine speed is demonstrated. The representative, hardware-in-the-loop (HIL) approach of the IPTMS laboratory provides a cost-effective and flexible solution for research investigations, while still maintaining realistic hardware interfaces for testing performance, integration, and controls.

OVERVIEW OF THE LABORATORY TESTBED

The laboratory under development is intended to be a flexible testbed for investigating and understanding integration dynamics in aircraft power systems supplying high power, pulsed loads. The integrated laboratory components were selected to be representative of an aircraft power system at a relevant power scale. A top-level layout of the representative power system is shown in [Figure 1](#). In order to minimize cost while maintaining a flexible and representative research platform, hardware emulation is being utilized for both the engine and electrical loads. Using emulation for the turboshaft engine allows for the engine conditions to be readily changed, and for alternate engine control strategies to be more easily considered. The flexibility of the laboratory testbed will be a significant benefit as it continues to evolve to address a variety of research questions related to aircraft power system integration.

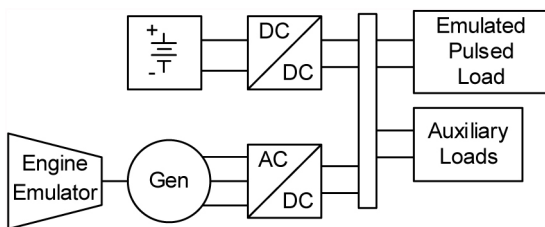


Figure 1. Top-level diagram of the laboratory testbed.

Description of the Physical Engine Emulation Setup

Within the laboratory testbed, the hardware setup specific to transient engine emulation is shown in [Figure 2](#). At present, the turbine engine dynamics and the rotor dynamics of the coupled power turbine and generator are represented by two real-time systems working in tandem. This approach was selected since the real-time engine emulator was delivered with the assumption that the customer would supply power turbine shaft speed as an input. An alternative approach that is often used (and could be used in the future) is to combine the engine model and rotor dynamics into a single real-time model running on a single real-time platform. Using either approach, the interface as seen by the drive stand will be identical.

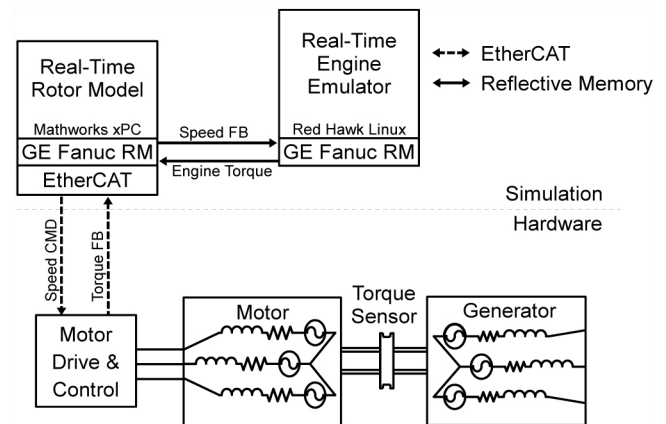


Figure 2. Block diagram of the HIL, engine emulation system.

As noted in [Figure 2](#), the two simulation systems employ real-time environments. The engine emulator uses Red Hawk Linux which couples a desktop-like environment with tight control over real-time priority threads. The engine model is using a soft real-time clock meaning that if an execution overrun occurs the system uses the last calculated value rather than halting the entire system. The engine emulator's execution speed is 5 ms.

Communication between the engine and rotor emulators is achieved using GE's FANUC reflective memory (RM) card as a data sharing pool. The rotor emulation system is a Speedgoat machine running Mathworks' xPC Target, which uses a host/client approach requiring model deployment from the host. This real-time environment is based on a DOS-like operating system that allows no direct interaction, thus requiring a host. Speedgoat is a turnkey solution for Mathworks' xPC Target environment. The rotor model execution speed is set to 1 ms, which provides an appropriate update rate for the drive stand.

Communication with the drive stand is achieved via EtherCAT. EtherCAT is a deterministic protocol that utilizes a master/slave approach allowing a single master with many slaves. In the implemented hardware system, the drive stand is the master, meaning that the rest of the EtherCAT network devices must be slaves. The rotor emulation machine has the functionality to be a slave on an EtherCAT network using a HiScer slave.

EtherCAT card and drivers developed by Speedgoat. These communication technologies and machines close the control loop between the drive stand and the engine emulator.

Based on the model execution speeds described earlier, control and feedback latencies will be briefly discussed assuming the worst case scenario (longest possible latency). The latencies include model execution time as well as data communication latencies for each leg of the command/feedback signal. The reflective memory is considered to have zero communication latency considering it is several orders of magnitude faster than the model time steps. For a torque from the engine emulator to be translated to a speed command and reach the drive stand, the latency is 2.05 ms. A breakdown of that latency is 2 ms for read/calculate/write actions on the Speedgoat and 50 μ s for the EtherCAT communication latency. The latency of a feedback signal from the drive stand translating to a speed seen by the engine emulator has a max value of 7.05 ms. This latency includes the 50 μ s EtherCAT communication latency, 2 ms for read/calculate/write actions on Speedgoat, and 5 ms for the engine emulator to read the feedback signal on the reflective memory card. Considering each system contains asynchronous loops, the latencies described above could be less depending on the current loop position.

The drive stand used to emulate the engine consists of two low-inertia, 330 kW permanent magnet AC motors and two variable speed drives. The motors can be coupled together to provide a combined continuous power output of 660 kW at their rated speed of 32000 rpm. For the generator currently under investigation, the combined power output of the drive stand is required. The motors are also capable of 150% overload for 60 s or 200% overload for 3 s. This overload capability combined with the low-inertia of the motors will prove to be beneficial when emulating gas turbine engines.

The test stand is equipped with a 500 Nm dynamic torque sensor situated at the interface of the drive stand and the generator under test. The torque sensor is documented to have 10 kHz bandwidth (~ 3 dB). An understanding of the generator torque measurement and torque sensor dynamics is necessary for successful engine emulation. This will be discussed further in the next section.

COUPLED ROTOR MODEL

The coupled rotor model provides the critical link between the modeled dynamics of the engine and the measured dynamics of the generator under test. The rotor model also handles scaling of power and speed between the generator and engine since the representative laboratory equipment was not originally specified to directly couple to the selected engine. As a first step in describing the link between hardware and simulation, the power/speed scaling will be neglected, and thus, the rotor model can be represented as shown in Figure 3. At its heart, the model is simply an implementation of Newton's

Law of Rotational Motion; however, one must pay special attention to the measured torque in order to capture the dynamics appropriately.

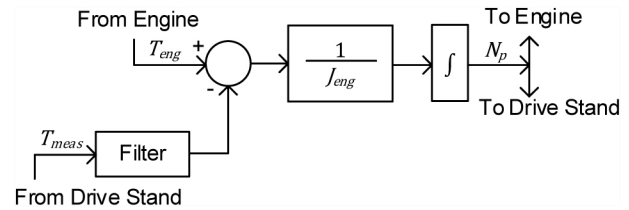


Figure 3. Block diagram of basic rotor model used in the HIL setup.

The block diagram representation in Figure 3 is given in terms of the measured shaft torque. Breaking down the total measured torque into separate torque terms, the rotor dynamics (without considering scaling) can be equivalently represented as follows,

$$T_{eng} - T_{e,gen} - T_{loss,gen} = (J_{eng} + J_{gen}) \frac{dN_p}{dt} \quad (1)$$

where T_{eng} is the total torque placed on the shaft due to the engine, $T_{e,gen}$ is the electromagnetic torque of the generator, $T_{loss,gen}$ is the torque due to mechanical losses in the generator, J_{eng} and J_{gen} are the engine and generator inertia terms, respectively, and N_p is the power turbine speed. The sign convention for the torque is such that the generator electromagnetic torque, mechanical losses, and the acceleration of the shaft are all seen as a load from the perspective of the engine. As made clear by the equation, the coupled shaft is assumed to be infinitely stiff.

From the real-time engine model, the rotor model receives total engine torque (including the effect of mechanical loss) as an input. The speed calculated by the rotor model is then fed back to the engine model. In particular, the speed is used by the Full Authority Digital Electronic Control (FADEC) controller, which is currently set up to govern to a low pressure (LP) spool speed determined by the throttle.

From the emulator hardware, the rotor model receives the measured torque value. The test stand's dynamic torque sensor will read the sum of torque on the generator side of the shaft (or equivalently, the sum of torque on the drive stand side). The total measured torque is given by,

$$T_{meas} = T_{e,gen} + T_{loss,gen} + J_{gen} \frac{d\omega_{rm}}{dt} \quad (2)$$

where ω_{rm} is the generator mechanical speed, which is assumed to be equivalent to N_p when speed scaling is neglected. The measured torque could be equivalently written in terms of drive stand quantities, essentially replacing the subscript *gen* with one indicating the drive stand. The presence of inertial torque in the measured signal can be verified by