AFRL-RZ-WP-TP-2009-2154

EFFECTS OF TRANSIENT POWER EXTRACTION ON AN INTEGRATED HARDWARE-IN-THE-LOOP AIRCRAFT/PROPULSION/POWER SYSTEM (POSTPRINT)

Michael Boyd, John McNichols, Mitch Wolff, Michael Corbett, and Peter Lamm

PC Krause and Associates, Inc.

NOVEMBER 2008

Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
PROPULSION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YY)***
November 2008

2. REPORT TYPE
Journal Article Postprint

3. DATES COVERED ***(From - To)***
01 November 2008 – 01 November 2008

4. TITLE AND SUBTITLE
EFFECTS OF TRANSIENT POWER EXTRACTION ON AN INTEGRATED HARDWARE-IN-THE-LOOP AIRCRAFT/PROPULSION/POWER SYSTEM (POSTPRINT)

5a. CONTRACT NUMBER
FA8650-04-D-2409-0004

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

6. AUTHOR(S)
Michael Boyd, John McNichols, and Mitch Wolff (PC Krause and Associates, Inc.)
Michael Corbett and Peter Lamm (AFRL/RZPE)

5d. PROJECT NUMBER
3145

5e. TASK NUMBER
32

5f. WORK UNIT NUMBER
314532ZF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

PC Krause and Associates, Inc.
3000 Kent Avenue, Suite C1-100
West Lafayette, IN 47906-1075

Electrical Technology and Plasma Physics Branch (AFRL/RZPE)
Power Division
Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson AFB, OH 45433-7251
Air Force Materiel Command
United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RZPE

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RZ-WP-TP-2009-2154

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
This article was presented at the SAE Power Systems Conference, 11-13 November 2008, Bellevue, Washington (Paper number: 2008-01-2909. PAO Case Number and clearance date: 88ABW-2008-0408, 09 October, 2008.

14. ABSTRACT
As aircraft continue to increase their power and thermal demands, transient operation of the power and propulsion subsystems can no longer be neglected at the aircraft system level. The performance of the whole aircraft must be considered by examining the dynamic interactions between the power, propulsion, and airframe subsystems. Larger loading demands placed on the power and propulsion subsystems result in thrust, speed, and altitude transients that affect the aircraft performance and capability. This results in different operating and control parameters for the engine that can be properly captured only in an integrated system-level test. While it is possible to capture the dynamic interactions between these aircraft subsystems by using simulations alone, the complexity of the resulting system model has a high computational cost. This paper investigates the possibility of using hardware-in-the-loop (HIL) power extraction with real time simulation of the airframe and propulsion subsystems.

15. SUBJECT TERMS
hardware-in-the-loop, transient, turbine engine, simulation, airframe, six degree of freedom

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Michael Corbett
Unclassified	Unclassified	Unclassified	SAR	14	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

2008-01-2926

Effects of Transient Power Extraction on an Integrated Hardware-in-the-Loop Aircraft/Propulsion/Power System

Michael Corbett, Peter Lamm
Air Force Research Laboratory

John McNichols, Michael Boyd, Mitch Wolff
PC Krause and Associates, Inc.

ABSTRACT

As aircraft continue to increase their power and thermal demands, transient operation of the power and propulsion subsystems can no longer be neglected at the aircraft system level. The performance of the whole aircraft must be considered by examining the dynamic interactions between the power, propulsion, and airframe subsystems. Larger loading demands placed on the power and propulsion subsystems result in thrust, speed, and altitude transients that affect the aircraft performance and capability. This results in different operating and control parameters for the engine that can be properly captured only in an integrated system-level test.

While it is possible to capture the dynamic interactions between these aircraft subsystems by using simulations alone, the complexity of the resulting system model has a high computational cost. This paper investigates the possibility of using hardware-in-the-loop (HIL) power extraction with real time simulation of the airframe and propulsion subsystems. This method captures the interdependency of engine performance during transient shaft loading (to produce electrical power) and aircraft system-level changes that result from the same power extraction. The dynamic interactions between aircraft subsystems highlight the need for system-level analysis using a combination of high-fidelity computer models and hardware in a real-time environment to fully and accurately understand system-level capabilities and stability.

INTRODUCTION

Aircraft are becoming increasingly more complicated and tightly integrated systems of subsystems. This integration presents the possibility of non-linear, time-dependent interactions between the aircraft subsystems. Historically, these interactions have been neglected, with each subsystem being designed, analyzed, and tested with little consideration for system-level integration. Steadily increasing power and thermal load requirements are responsible for drastically increasing the magnitude of the dynamic interactions that exist between aircraft subsystems. Though optimization has traditionally taken place at the component or subsystem level, non-linear interactions suggest that optimization must be done instead at an aircraft system level. This system-level performance optimization requires advanced modeling, simulation, and integration techniques.

Specific to the interaction between aircraft engine and power subsystems, shaft horsepower extraction from the engine has the potential to introduce torque ripple, high mechanical stress, and speed transients. These effects can in turn cause compressor stall and unacceptable thrust transients. The same power extraction has the potential to create problems with the power subsystem as well. For example, large excursions in shaft speed outside of the generator rated operating range can result in voltage or current transients that may cause overheating or mechanical stresses thereby reducing the life of the electrical generation system. In addition, these transients may affect the power quality of the aircraft main bus, thereby impacting the electrical loads such as the radar or actuation and may result in a source transfer to back-up generation or batteries.

The coupling between the aircraft engine and airframe is realized by considering the interdependency between thrust and operating conditions such as altitude and Mach number. The available thrust is a function of altitude and Mach number (and other variables) and the ability to attain a desired Mach number and altitude are dependent on the available thrust. Furthermore there is a control coupling between the throttle lever angle (TLA) and the thrust produced (subject to shaft loading and the operating conditions mentioned previously). As the aircraft autopilot changes the TLA to try to complete its mission, it can introduce unpredictable throttle transients that can affect engine stability and performance. In addition there may be thermal management issues at the component, subsystem, or system level that are also coupled to the airframe, engine, and power subsystems.

To properly consider dynamic interactions between aircraft subsystems, a multi-physics system simulation must be used. Computer models of different components and subsystems are often developed by different entities, which can lead to issues when trying to integrate models. Intellectual property must be protected while allowing appropriate variables to pass between models. Enabling models to communicate with each other at all is a non-trivial issue when they are developed in different languages or programs. Distributed Heterogeneous Simulation (DHS) is a software tool that synchronizes any number of dynamic simulations in a wide variety of languages and modeling environments[1]. It allows each model to run in its own native environment on whichever platform (Windows, Linux, etc.) it prefers. In this way, DHS protects the proprietary details of each model while allowing it to become part of a larger system-level simulation and can provide significant increases in simulation speed[1].

Although DHS addresses the integration of multi-physics, multi-vendor subsystem models in a variety of languages, such a paradigm can have limitations with respect to real-time simulation. If the provided component subsystem models do not execute faster than real-time or if the system dynamics require significant bandwidth, the integrated system simulation speed may not be sufficient. This is especially problematic when coupling models that are interested in drastically different time scales. An example would be coupling a detailed generator model (time steps on the order of microseconds), an engine model (time steps on the order of milliseconds), a thermal management model (on the order of seconds or minutes), and a flight mission controller (on the order of hours). In this scenario, getting meaningful flight mission controller data would require the generator model to execute for hours of simulation time which may equate to several days of execution time.

Practical system-level integration requires using an alternative or complementary solution. One such approach is hardware-in-the-loop (HIL). This technique integrates one or more simulations with tangible pieces of hardware. In order to perform a meaningful HIL test the system must run exactly real-time – the only useful execution rate for hardware. The real-time constraint presents benefits and challenges. When a simulation of a system component/subsystem is used, the model complexity must be limited to ensure that the system maintains real-time execution speed at every time step. Furthermore, the model must be compatible with a real-time operating system that is capable of running the simulation. For some models, especially those that use large time steps, real-time simulation might force a model to run orders of magnitude more slowly than the computational limit of the computer. However, HIL also enables hardware to be used in place of models whose complexity would render it impossible to meet real-time simulation constraints. HIL facilitates the ideal combination of hardware and software as long as it is possible to properly interface each piece into a whole system.

The approach used in this paper leverages both the DHS software tool and the HIL integration of simulations with hardware components/subsystems. While the details of configuring the hardware and software for this system-level test are outside the scope of this paper, it is prudent to provide an overview for a more complete understanding of the test configuration. Simulations of an engine and its Full Authority Digital Engine Control (FADEC), along with a 6 degree-of-freedom (6DoF) airframe dynamics model and its autopilot flight controller are used. A generator is used as the hardware component in the loop for the system-level studies. The next section discusses each of these subsystems in more detail. Then, the software/hardware integration at the system-level is described in a separate section for a clear understanding of the HIL approach used for the results presented in this paper.

AIRCRAFT DYNAMIC SUBSYSTEMS

DYNAMIC ENGINE MODEL - The generic turbine engine model utilized in this investigation is based upon the model developed by Gastineau[2] in MATLAB/Simulink. It has not been validated with detailed experimental data, but is considered a generic framework from which specific engine types can be derived. The engine model is based on a lumped component approach for ease of modification and replacement of engine components. Each component is created with its own set of inputs and outputs. The components and their interactions are developed and modeled based on fundamental laws of physics such as the conservation of mass, momentum, and energy. However, to simplify the turbomachinery modeling, components such as a multi-stage turbine or compressor are simulated as a single component. This approach is adopted because turbine and compressor maps are generally created in a lumped fashion rather than stage-by-stage. Similarly, the combustor simulates combustion of a lumped amount of fuel and air in a control volume. It does not simulate the flame distribution or flame dynamics of the combustion process and instead assumes ideal mixing and complete combustion.

The engine modeled for this paper is a two-spool, high-bypass turbofan engine in the 8,000 pound thrust class designed for high altitude, subsonic operation. A key feature of the Air Force Research Laboratory (AFRL) model is its ability to simulate transient operation. Transient modeling, in addition to steady state analysis, is vital in the testing and design of turbine engines. Dynamic simulations capture overshoot characteristics of a turbine engine which could cause the engine to fail even though a steady state analysis would suggest survival.

The AFRL generic turbine engine model has been designed to be flexible. The component maps and engine layout can easily be changed to model various engine types. The controller that is used can also be changed and updated as needed. In its current configuration, the generic turbine engine model's FADEC is included in the same simulation and runs primarily on a target fan speed limit but is subject to other control loops such as maximum turbine inlet temperature limits.

Different operating points can be specified by the user to examine the performance of the engine. Input variables of the turbine engine model as a standalone simulation include TLA, high pressure (HP) and low pressure (LP) turbine loads, altitude, and Mach number. When integrated with the airframe dynamics model, TLA, altitude, and Mach number are no longer completely independent and the LP load is driven by the LP generator hardware. Although the engine model allows the user to monitor any engine variable, this paper focuses on the LP spool speed, power load on the LP and HP spools, thrust, and high pressure compressor (HPC) surge margin.

AIRFRAME DYNAMICS MODEL - The 6DoF model used in this study is the flight path generation package Bluemax[3]. Bluemax is a data based Fortran model that incorporates the equations of motion to calculate rotation and translation in 3-dimensional space. While the model is capable of analyzing takeoff and landing conditions, the tests presented in this paper assume a steady flight starting condition. The Bluemax model includes a flight mission autopilot controller. This can be used to program waypoints that define a mission. For this paper, the heading was held constant such that the aircraft did not deviate in the longitudinal direction. In this way, the waypoints were used to define changes in target altitude and Mach number as a function of latitudinal distance traveled. This method was used so that the effects of the transient load could be linked to dynamic flight changes in a clear way.

Bluemax can be used to consider flight dynamics of any conventional aircraft by simply providing the appropriate physical and performance characteristics data. For this investigation, the 6DoF model simulates a high altitude, subsonic, single engine aircraft using an existing non-proprietary dataset. In its native configuration, Bluemax uses a lookup table to compute thrust as a function of altitude, Mach number, and TLA. The autopilot then adjusts the TLA in an attempt to get the required thrust to complete the mission. For the coupled system investigated, the lookup table is eliminated and the thrust is provided by the engine model.

POWER SUBSYSTEM HARDWARE – The power subsystem hardware consists of a prototype LP generator and a representative load. The HP spool of the engine can be loaded "electrically" only in simulation in the current configuration. The HP spool load was held at a constant value of 15 kW, but the LP spool load was allowed to change dynamically using the aforementioned hardware. The LP generator is physically mounted on a 350 horsepower motor drive stand that emulates the LP spool of the engine. The generator is wired electrically to a representative load, which in this configuration is a collection of resistors that can be triggered independently. The configuration command for the load bank (which governs the amount of power being extracted from the generator) can be sent in real-time with very little switching latency.

AIRFRAME DYNAMICS, PROPULSION, AND POWER SUBSYSTEM INTEGRATION

The 6DoF and turbine engine models are connected using Distributed Heterogeneous Simulation (DHS) to pass variables between the two models. As shown in Figure 1, the fuel burn rate and thrust are sent from the engine model to Bluemax; the operating conditions (altitude and Mach number) and throttle setting (TLA) are sent from Bluemax back to the engine. As mentioned previously, the FADEC and engine are combined into one simulation and are collectively referred to as "the engine." The Simulink engine model is compiled using Real-Time Workshop for a National Instruments LabVIEW Real-Time 8.5.1 system with the DHS communication links included. Similarly, the aircraft autopilot controller is incorporated as part of the Bluemax 6DoF model and the code is compiled with the DHS links for communication. Rather than on a real-time system, Bluemax runs on a PC running Windows XP, where it is still capable of running faster than real-time. DHS does

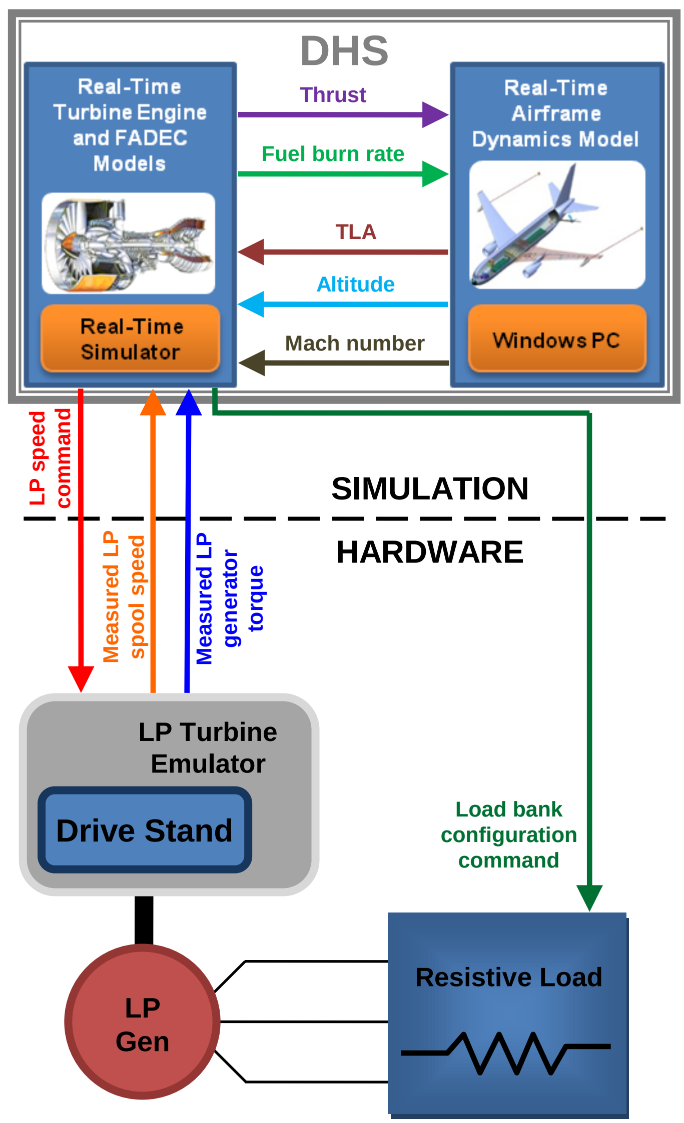

Figure 1. Hardware-in-the-Loop Configuration

not automatically force real-time simulation (which is a requirement for HIL analysis); the DHS software merely synchronizes the models in simulation time. System-level real-time simulation is accomplished by running the engine model in hard real-time on the National Instruments real-time computer. Since it communicates with the 6DoF model in a simulation time synchronized manner, the entire simulation therefore meets the real-time requirement.

Figure 1 also shows the communication between the simulated subsystems and the power subsystem hardware. The motor drive stand, which emulates the LP spool of the engine, is given an analog voltage speed command from the I/O board of the real-time computer that runs the engine model. It tracks the spool speed calculated by the model in real-time. The engine model also uses its I/O board to send out a series of digital signals that define the load bank configuration. The load bank puts a resistive load on the generator which creates a torque on the drive stand shaft. This torque is measured with a torque transducer and is sent back to the engine model as an analog voltage. After converting this signal properly, the feedback torque is used in model calculations to determine the spool speed at the next time step. A magnetic pickup speed transducer also captures the rotational speed of the drive stand. This signal is sent through a frequency-to-voltage conditioner and then is passed to the engine model as well. This signal is used to capture drift between commanded and actual speed as well as lag in the speed response.

RESULTS

Verification of the HIL approach to system-level analysis was done in previous work to ensure that the system both properly captures the dynamic interactions between aircraft subsystems and that the drive stand is capable of tracking the calculated (commanded) spool speed.[4-7] Once confidence in using HIL for system-level testing was established, a suite of tests was designed to exercise the coupled dynamics between the aircraft propulsion, power, and airframe subsystems. It is important to note that though the LP power extractions are less than 100 kW, this represents a substantial portion of total available engine power at high altitudes for the modeled engine. For each test, a constant 15 kW load is assumed on the HP spool of the engine. For the coupled models (i.e. the 6DoF and engine models exchange variables), the same starting fuel mass is assumed to be on board the aircraft.

DECENT CONFIGURATION – The first study is a descent test where the autopilot attempts to descend smoothly from a steady altitude of 60,000 feet to a new altitude of 59,000 feet at a constant Mach number of 0.6 with a minimum pitch limit of -1.0° (to allow a smooth descent). A large power load is extracted from the LP generator during the descent and the results are shown in Figures 2 through 4.

Figure 2 investigates the dynamic interactions between the airframe and the engine during the descent when a power extraction transient is introduced. Those dynamics are compared with assumptions made when using the engine model alone. Two data sets are presented in this figure. One data set shows the response of the engine model without communicating variables to and from the Bluemax 6DoF model (*Engine Only Descent*). For that scenario, a constant descent rate is used and the TLA and Mach number are assumed to be constants during the whole test. The second data set shows the response of the system when using the engine model coupled to the 6DoF model (*6DoF/Engine Descent*). In both cases, an LP generator load of 74.4 kW (requiring about 82 kW of shaft power) is turned on just before the target altitude of 59,000 feet is reached. It can be seen in the first subplot of Figure 2 ("Altitude (kft)") that the constant descent rate assumption is not perfect, but is still a very reasonable approximation for the true behavior of the system.

The second subplot of Figure 2 ("Mach Number") shows that the constant Mach number assumption is less valid (though still less than 5% off). The droop in Mach number is explained by examining the remaining two subplots of Figure 2. The autopilot backs off the throttle to start the descent as seen in the third subplot ("TLA (%)"). The lower TLA causes the engine to produce less thrust (the fourth subplot). Just as the aircraft is reaching its target altitude, the LP load is turned on at the location indicated by the orange line that cuts through all subplots of Figure 2. The LP load results in a further thrust drop which causes the aircraft to lose airspeed (Mach number shown). To compensate, the autopilot quickly adjusts to a full throttle command to recover the lost speed and return to its target altitude and Mach number. The engine eventually ramps up to a high thrust state at the full throttle condition, but then the throttle is cut back because the aircraft reaches its target operating point. The autopilot controller oscillates its commanded TLA and finally steadies out at about 96% throttle. The

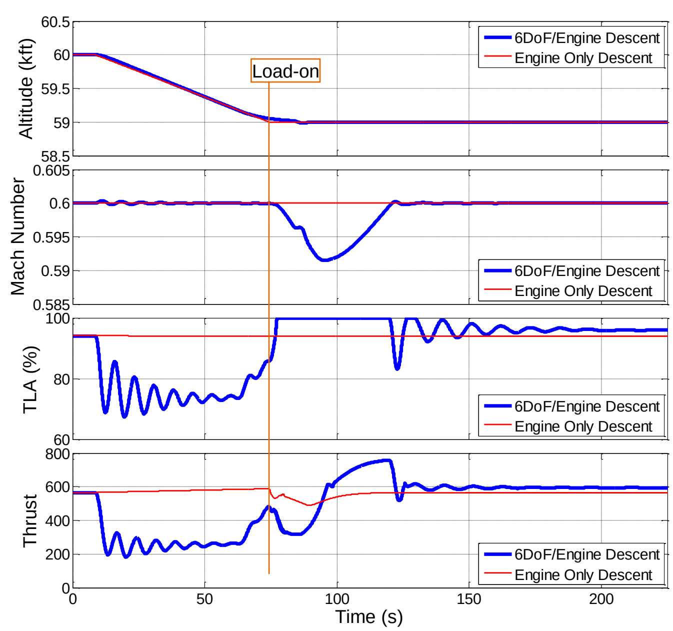

Figure 2. Descent Test – Dynamic Interactions

oscillations in the other variables are similarly damped out and the system reaches steady flight with the load on.

This figure shows that while reasonable approximations can be made for the altitude and Mach number for such a descent test, there is no way to make a reasonable assumption about the TLA. The TLA, in turn, has a drastic effect on the engine performance (as illustrated by the "Thrust" subplot in Figure 2) and engine stability (to be addressed next).

Figure 3 presents the LP Spool Speed as a function of time for the same descent from 60,000 to 59,000 feet. Three different data sets are presented. One data set is the same as in Figure 2 –descent under autopilot control for the engine model coupled to the 6DoF model where the load is applied just before the target altitude is reached (labeled as *6DoF/Engine (Late)* in Figure 3). The second data set is when the 6DoF and engine models are coupled and under autopilot control during the descent, but the LP load is turned on just after the descent starts (*6DoF/Engine (Early)*). For the third data set (*Engine Only (Early)*) the engine assumes the same descent profile as in Figure 2 (for an engine only analysis) and the LP load is applied just after the descent starts.

It can easily be seen in Figure 3 that the time at which the LP load is turned on has a drastic effect on the system response. In fact, for the coupled models case when the LP load is applied just as the descent starts (*6DoF/Engine (Early)*), the engine fails. This happens because the engine is at such a low power setting (~70% TLA) just after the descent starts. The power extraction is initiated near that TLA local minimum and there is insufficient shaft power for the generator's load. The problem is compounded because the TLA increases sharply from that minimum. The entire system simulation becomes unstable at this point and the test ends prematurely. The *Engine Only (Early)* data, on the other hand, shows that the assumptions made when running the engine model alone are not accurate. The *Engine Only (Early)* data artificially predicts stability for the case when the load is applied just as the descent starts, primarily due to the assumption of a constant TLA that provided sufficient power to sustain the load on the LP generator.

Besides illustrating the influence load application timing has on engine stability, Figure 3 also shows that it is crucial to include all three subsystems – the engine, the airframe, and the LP generator – to properly capture the system behavior. There are clearly unpredictable dynamics happening as the autopilot tries to achieve its mission without consideration for engine operation. The system-level test is required to understand the compounding effects of coupled subsystem dynamics.

Figure 4 shows the high pressure compressor (HPC) surge margin for the same descent test and same data sets as Figure 3. The HPC surge margin is a measure of flow stability within the compressor. While compressor stall and surge are often recoverable conditions, the engine and FADEC simulations used in this study do not have the required control algorithms for recovery. For this reason, 0% HPC Surge Margin is considered engine failure, and a successful test cannot have compressor surge. This is a reasonable approach since it is generally not desirable to operate an engine at the edge of its stable operating envelope anyway. This figure illustrates the tight non-linear, dynamic coupling between the power, propulsion, and airframe subsystems of the aircraft and shows that survivability of the system can be more accurately predicted by performing analyses at a system-level. As mentioned in the discussion of Figure 3, making assumptions about the interactions between the engine and other aircraft subsystems can lead to a false sense of security by over predicting stability (i.e. the *Engine Only (Early)* data set suggests stability). It is also prudent to mention that when the LP load is turned off (~230 s), there is an overshoot in LP spool speed (Figure 3) and HPC Surge Margin (Figure 4). The TLA assumptions made by the *Engine Only (Early)* tests create a smoothing effect that over predicts the maximum speed overshoot and misses oscillations in both the surge margin and LP spool speed.

ASCENT CONFIGURATION – Another set of figures (Figures 5 through 7) demonstrates a different effect of

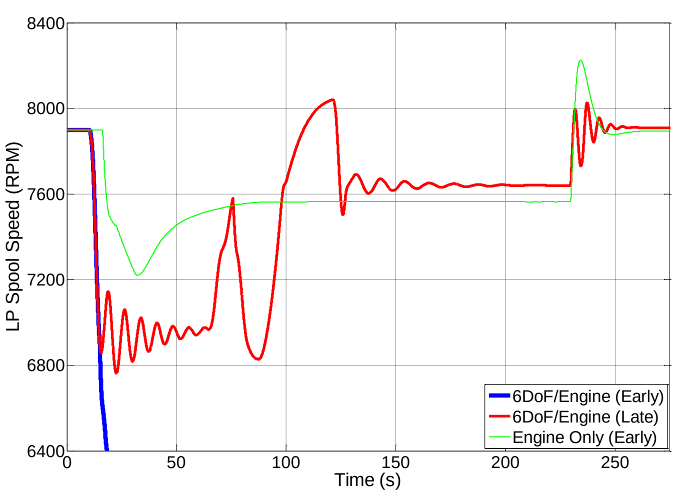

Figure 3. Descent Test – LP Spool Speed vs. Time

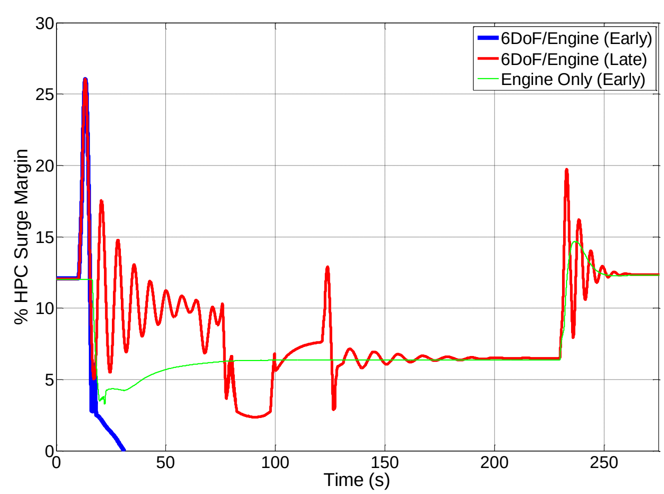

Figure 4. Descent Test – HPC Surge Margin vs. Time

the system-level dynamics. This study shows that the engine can actually be more stable and more capable during a climb than at steady flight. This study compares a climb in altitude from 60,000 to 62,000 feet to steady flight at each of those altitudes. Again, the steady-state Mach number at both altitudes is 0.6 and there is a constant 15 kW of power being extracted in simulation from the HP spool of the engine throughout the test. An LP step load of 66.9 kW of electrical power (requiring about 74 kW of shaft power) is put on the generator in each case.

The first subplot in Figure 5 (showing LP spool speed as a function of time) suggests that during steady flight at 60,000 feet and 0.6 Mach, a step LP power extraction

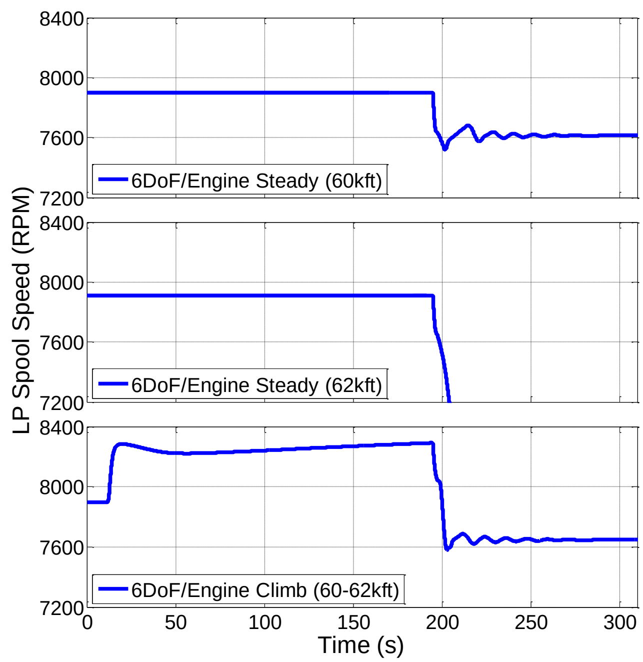

Figure 5. Ascent Test – LP Spool Speed vs. Time

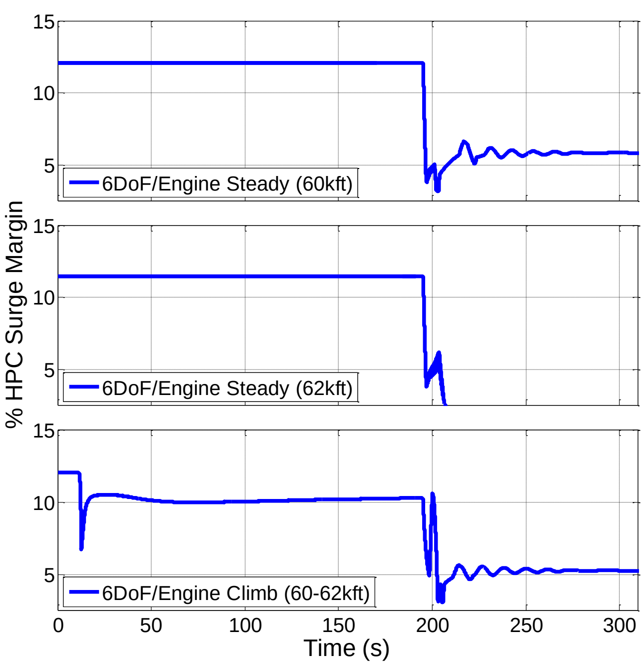

Figure 6. Ascent Test – HPC Surge Margin vs. Time

does not cause concern for system stability. In contrast, the second subplot suggests that the engine is not capable of sustaining the same step power load at a constant altitude of 62,000 feet. Figure 6 further illustrates this point by showing the HPC Surge Margin for the same set of tests. In the first subplot of Figure 6, it is apparent that the engine is capable of being dynamically loaded and then stabilizing at 60,000 feet. The second subplot shows that the engine is not capable of sustaining that LP load at the higher altitude.

The third subplot (in Figures 5 and 6) shows that if the same aircraft is in a climb from 60,000 to 62,000 feet and the load is applied at the target altitude just before the Mach number reaches its target of 0.6, the system is stable. Figure 7 considers the variables that are passed between the engine model and the 6DoF model (altitude, Mach number, TLA, and thrust) to more clearly illustrate why the aircraft is able to sustain an LP step load during the climb. Two data sets are presented in each of the subplots – the steady flight at 62,000 feet, *6DoF/Engine Steady (62kft)*, (which fails just after the LP load is applied) and the successful climb from 60,000 to 62,000 feet, *6DoF/Engine Climb (60-62kft)*.

It can be seen in the first subplot of Figure 7 that the aircraft is able to quickly climb (though limited by the autopilot to a maximum pitch angle of 7°) the 2,000 feet to its target altitude and then hold it for the duration of the test. The *6DoF/Engine Steady (62kft)* data shows that the aircraft is able to maintain altitude from before the load was applied until the test failed. The second subplot shows that there is a significant drop in the aircraft Mach number as it tries to climb altitude. It takes much longer to recover the speed than to climb in altitude. Once the target Mach number of 0.6 is reached, there are only slight ripples as the system steadies out. The *6DoF/Engine Steady (62kft)* data shows that the Mach

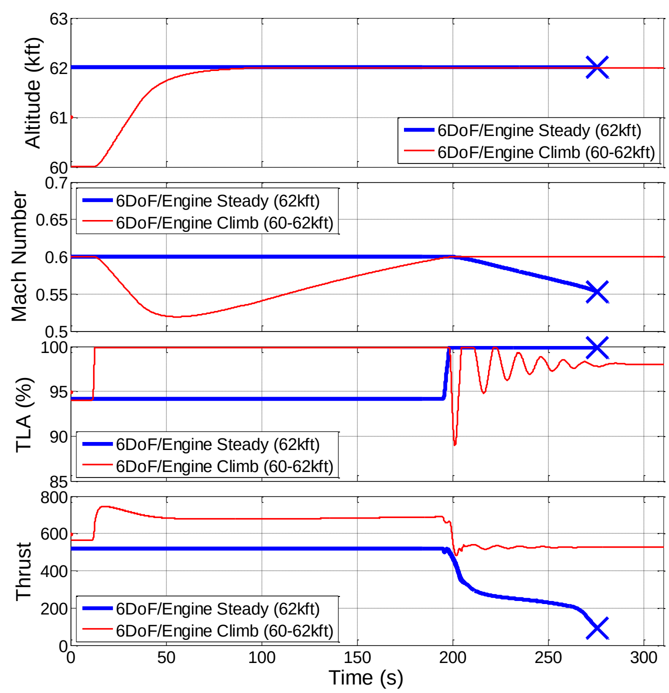

Figure 7. Ascent Test – Dynamic Interactions

number starts to fall from the point at which the LP step load is applied and continues to decrease until engine failure.

The third subplot is perhaps the most useful in Figure 7 because it shows why the climb provides stability. For the *6DoF/Engine Steady (62kft)* data set the TLA jumps to 100% in response to the load being turned on. Both a “throttle slam” and a step load are operations that are very difficult for the engine. The combined effect of the LP load turn-on transient and the “throttle slam” reaction of the autopilot (to request increased thrust so altitude and Mach number are maintained) is more than the engine can handle. On the other hand, during the climb test, the autopilot controller has already been commanding full throttle (to get back to the target Mach number) when the LP load is turned on. Then, with a higher total engine power (at the higher TLA), the engine is able to survive the LP load turn-on transient. The fourth subplot in Figure 7 shows the engine thrust. As expected for the *6DoF/Engine Climb (60-62kft)* test, the thrust drops from the maximum engine thrust (before the load is applied) to a lower final value since the TLA is less than 100% and the LP spool is loaded. Also as anticipated, the *6DoF/Engine Steady (62kft)* test shows the thrust continue to drop off from the point of the LP load turn-on until engine failure.

CONCLUSION

An advance in system-level modeling has been made in this effort by capturing the dynamic interactions between an aircraft propulsion subsystem (engine with FADEC), power subsystem (generator and representative load), and the airframe. It has been shown that there is an unpredictable connection between aircraft stability and engine stability when loaded transiently under autopilot control. This paper shows that making approximations or assumptions for the effect of the autopilot controller on the control of the engine can over and under predict stability. The dynamics between the TLA and the resulting thrust are too difficult to predict without coupling the models for real-time simulation. Also, only the coupled simulations with HIL LP power extraction can identify the ability of a climb operation to stabilize the engine during the load-on transient.

ACKNOWLEDGMENTS

This research was conducted at the Modeling, Simulation, and Analysis Team (MSAT) Laboratory. The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or U.S. Government.

The authors give special thanks to Tom Greene whose time and knowledge enabled the successful completion of the testing required for this effort.

REFERENCES

1. C. E. Lucas, E. A. Walters, J. Jatskevich, O. Wasynczuk, and P. T. Lamm, “A Distributed Heterogeneous Simulation of a Representative Aircraft Power System”, *2002 SAE Power Systems Conference Proceedings*, October 2002, Coral Spring, Florida.
2. Z. Gastineau, “Robust Internal Model Turbomachinery Control,” Ph.D. Dissertation, Mechanical Engineering Department, Southern Methodist University, Dallas, Texas, 1998.
3. “BLUEMAX 5 User’s Manual”, SURVIAC, August 2007, Wright-Patterson AFB, Ohio.
4. S. Ramalingam, A. Green, P. Lamm, H. Barnard, E. Walters, J. Wells, “Integrated Hardware-in-the-Loop Simulation of a Complex Turbine Engine and Power System”, SAE Paper 2006-01-3035, *2006 SAE Power Systems Conference Proceedings*, November 2006, New Orleans, Louisiana.
5. M. Corbett, J. Williams, M. Wolff, E. A. Walters, J. Wells, and P. Lamm, “Transient Turbine Engine Modeling and Real-Time System Integration Prototyping”, SAE Paper 2006-01-3040, *2006 SAE Power Systems Conference Proceedings*, November 2006, New Orleans, Louisiana.
6. M. Corbett, P. Lamm, K. Miller, J.M. Wolff, and E. Walters. “Transient Analysis of an Aircraft/Propulsion System with Hardware-in-the-Loop Power Extraction.” AIAA Paper 07-5114, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 2007.
7. M. Corbett, P. Lamm, P. Owen, S.D. Phillips, M. Blackwelder, J.T. Alt, J. McNichols, M. Boyd, and J.M. Wolff. “Transient Turbine Engine Modeling with Hardware-in-the-Loop Power Extraction.” AIAA Paper 08-5932, 6th International Energy Conversion Engineering Conference (IECEC), July 2008.