Hardware Development for the Controlled Fault Injection into a Turbofan Engine Air-Bleed Valve

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ABSTRACT

Gas path fault diagnostics assists operators in determining, and managing the health of gas turbine engines. Engine data depicting fault progression under realistic operating conditions is useful for the maturation of these diagnostic methods. In this paper we present hardware created to inject a progressive fault in an air bleed valve of a high bypass turbofan engine during on-wing engine testing. The developed hardware interrupts and overrides the engine control computer's command of the valve and allows for the nondestructive, progressive off-schedule operation of the air bleed valve. Numerical simulation results based on NASA's Commercial Modular Aero-Propulsion System Simulation 40k are presented to illustrate representative changes in measured engine parameters that can be expected during such an experiment.

1. INTRODUCTION

Data-driven diagnostics and prognostics endeavor to determine the health of a system and predict the remaining useful life of that system. Data illustrating nominal operation and off-nominal operation is key to the development of these methods. However, run-to-failure data collected under typical operational environments and loads can be rare. In many cases, in-service data related to the failure of a specific component or system is either unavailable or opportunistic, and laboratory bench testing of the hardware may be infeasible or may not fully represent system-level effects.

In such cases, non-destructive failure testing of the integrated system may be necessary. This paper will present progress towards the successful seeded fault testing of an air-bleed system within an aircraft gas turbine engine for the benefit of diagnostic and prognostic methods.

Under the NASA Aviation Safety Program, NASA, in collaboration with the U.S. Air Force and other external partners, is demonstrating and maturing aircraft engine health management technologies through a series of stationary ground-based on-wing engine demonstrations known as Vehicle Integrated Propulsion Research (VIPR) testing (Hunter, Lekki, & Simon, 2014). VIPR provides a means to test and evaluate emerging health management technologies on an aircraft engine including new sensors and diagnostic algorithms. This series of tests is ongoing at the NASA Armstrong Flight Research Center / Edwards Air Force Base on a C-17 aircraft equipped with Pratt & Whitney F117 high bypass turbofan engines. The first and second VIPR tests, which occurred in 2011 and 2013 respectively, introduced non-damaging gas path fault scenarios into one of the engines installed on the aircraft. A third VIPR test (VIPR 3), is scheduled to occur in 2015.

During the VIPR 3 tests, a Prognostics and Decision Making (PDM) experiment will off-schedule the test engine's station 2.5 air-bleed valve while the engine is at realistic operational levels. This PDM experiment will require new hardware designed to interrupt and override the command of the valve from the engine's control computer. The hardware presented here allows for the controlled injection of a fault in the engine's station 2.5 air-bleed valve system. The fault is a progressive degradation of the air bleed valves pneumatic actuator.

Previous work within the aircraft engine health management community has shown how gas path diagnostics can assist in the identification of rapid or abrupt gas path system faults through the observation and analysis of available engine gas path measurement parameters ((Li, 2002) & (Volponi, DePold, Ganguli, & Daguang, 2003)). The intent of the PDM research to be conducted in VIPR 3 will focus on the diagnosis of incipient or gradual gas path system faults along with prognostic forecasting of evolution of the fault over some future time horizon. Aircraft engine simulations can be used for the initial development and evaluation of gas path fault diagnostic methods.

For the purpose of this paper, the NASA Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k) generic turbofan engine model will be used to illustrate the expected fault signature of a station 2.5 bleed fault. While not identical to the Pratt & Whitney F117 turbofan engine that will be tested during VIPR 3, C-MAPSS40k does provided representative outputs suitable for the development of gas path fault diagnostic methods for an engine in the same thrust category as the F117. Rinehart and Simon used C-MAPSS40k for the development of an integrated model-based architecture for performance monitoring and gas path fault diagnostics (Rinehart & Simon, 2014). Their use of a model-based approach for the diagnosis of engine gas path fault conditions, when applied to experimental data depicting normal station 2.5 air bleed valve operation and failed open conditions yielded the accurate detection of a steady state fault. Additionally, Boyle used far field acoustics with limited success in the identification of a fully failed station 2.5 air bleed valve (Boyle, 2014).

The structure of the paper is as follows. Section II describes the air-bleed valve system. Section III presents the approach to fault seeding, the overall setup of the air-Bleed valve Override Box (BOB), and its integration within the aircraft-engine system. Section VI discusses the fault modeling effort under taken prior to the experiment for the benefit of operations and data analysis. The paper closes with a conclusion in Section V.

2. THE AIR-BLEED VALVE SYSTEM

The station 2.5 air-bleed valve system allows airflow to exit the gas path of the engine at the low pressure compressor exit, ensuring proper airflow between the low and high pressure compressor. The 2.5 bleed system improves engine start-up and ensures operability over the operating range of the engine. The 2.5 air-bleed valve is also used by the engine's Electronic Engine Control (EEC) system to assist in the recovery from stall or surge conditions (Linke-Diesinger, 2008).

The system is comprised of a closed loop controller, an electrohydraulic servo valve (EHSV), a pneumatic actuator, a linear variable displacement transducer (LVDT) and the valve itself. The valve is an axial ring which can cover or expose the circumferential slots at the exit of the low pressure compressor. It is connected to the actuator through a linkage which redirects linear motion to circumferential motion. The position of the valve is determined by the EEC, which modulates valve position based on the temperature corrected fan speed, N1C2. The valve is commanded open at low power settings, and modulates closed as the engine increases in power. The valve is positioned with the EEC's closed loop controller, which commands the valve slew rate through EHSV and utilizes a LVDT for position feedback. During this process the EEC continually outputs the LVDT/valve position to the aircraft's ARINC 429 digital data bus.

In this case, re-creating the engine's 2.5 bleed system on a laboratory test bench was not possible due to the complexity of the system, component availability, and the need to use aviation fuel as the working fluid for the EHSV and actuator.

3. THE FAULT AND THE FAULT INJECTION HARDWARE

The fault to be introduced to the air-bleed valve system will simulate the progressive degradation of the valve actuator. Under the simulated fault condition, the actuator will be unable to maintain the desired valve position. This will produce a drift towards the failsafe position of the actuator, 100% open. This condition will degrade engine efficiency, but will not compromise the operability of the engine.

To begin the Prognostic and Decision Making portion of the testing, in which the station 2.5 bleed fault will be injected, the engine speed will be increased from idle to the experimental test point at which, the air-bleed valve position will be approximately 50% open. Next the operator of the Bleed valve Override Box (BOB) located in the cargo bay of the aircraft will override the command of the valve from the EEC and begin issuing new commands with an independent controller located within the BOB. Manually inputting each point in the degradation profile, the operator will take the valve from the

Figure 1. The Bleed-valve Override Box (BOB).

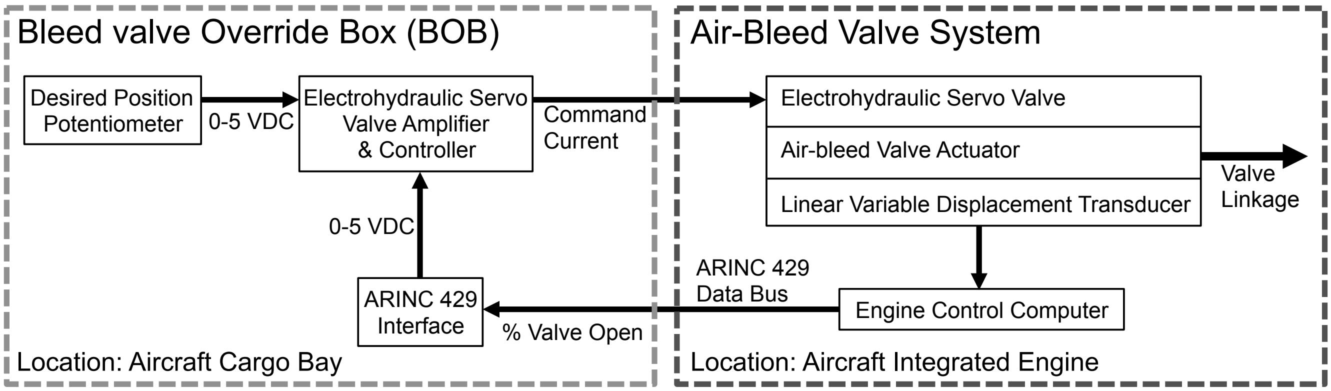

Figure 2. The modified feedback loop of the independent controller.

initial position commanded by the EEC based on N1C2 speed to a fully open failed state progressing at 5% increments with 3 minutes for the engine to stabilize between steps.

The BOB as shown in Figure 1 has been designed and developed to inject and control the progression of a fault in the overridden the air-bleed valve system. Enclosed within a vibration dampening, 10 unit high, 19" rack case, the BOB is composed of a power supply, a series of switches, an EHSV controller and error display, a positioning knob, and an ARINC 429 interface device. The power supply provides operational voltage for the controller, error display, and ARINC 429 interface device. The BOB includes an override switch which allows the control loop between the EEC and the EHSV to be overridden with a new control loop featuring the BOB's controller, the BD101 from Parker Controllers, providing proportional control of the EHSV. The controller generates a 10VDC reference voltage, which is attenuated by the desired position potentiometer/knob circuit to create a voltage signal ranging from 0VDC to 5VDC representative of the desired position of the valve. Finally, the ARINC 429 interface device, the Aeroflex DT400 ARINC 429 databus analyzer, is used to monitor the aircraft's databus for the dataword containing the valve's LVDT position. The ARINC 429 interface device interprets the data for the valve's current percent open position, and produces an analog voltage representative of that position. This signal is compared with the desired position voltage within the BOB's modified closed loop control of the valve. The controller error is displayed on a voltmeter mounted above the desired position knob.

From the BOB, located within the aircraft's cargo bay, a wiring harness with channels for the ARINC 429 databus, bleed-valve actuator inputs, EEC outputs, and LVDT circuit control will be routed across the wing of the aircraft to the engine pylon and down into the engine. With this implementation, the BOB operator is able to manually control the position of the station 2.5 bleed valve on the engine.

4. FAULT SIMULATION

Results from the NASA C-MAPSS40K turbofan engine simulation are presented in this section to examine the representative change in engine performance characteristics expected at each step in the station 2.5 bleed fault progression. C-MAPSS40k simulates the operation of a typical twin spool, high-bypass turbofan engine in the 40,000 pound takeoff thrust class, and has been tuned to produce data matching the characteristics of actual flight data (May, Csank, Lavelle, Litt, & Guo, 2010). While of the same thrust category as the Pratt & Whitney F117 turbofan engine to be used in the VIPR 3 test, C-MAPSS40k is not the same engine and therefore performance differences are expected. As such, the C-MAPSS40k results presented here are simply representative of the observations expected during the test. In conducting this assessment, C-MAPSS40k is run to a sea level static standard day condition (i.e., altitude = 0, Mach = 0, temperature = 59F) at an Engine Pressure Ration (EPR) power setting of 1.24. At this operating condition the C-MAPSS40k station 2.5 bleed valve is 50% open.

Within the simulation routine, the above operating point for the model is first specified, then the engine model is allowed to reach a steady-state at this setting. Next, in order to simulate degradation of the air-bleed valve actuator, the valve is operated off-schedule from the 50% open position towards 100% open in 5% increments. Between each increment, the engine is allowed to return to a stabilized steady state condition at the specified EPR power setting. Furthermore, during this progression, no other modifications where made to the model's closed-loop control system other than operating the station 2.5 bleed off-schedule.

In general, the take away from the data generated by the C-MAPSS40k simulation is a representation of the type of measurement changes that are to be expected during the PDM research and the relative magnitude of those perturbations. The station 2.5 bleed bias from 50% open to 100% open is most evident in percentage change of fuel flow (Wf) which showed a 3.3% increase, exhaust gas temperature (T50) which showed a 3.2% increase, and the station 2.5 pressure and temperature (P25 and T25) which decreased by 6.8% and 9.01% respectively. Fig. 3 plots the change in exhaust gas temperature (EGT) as a function of station 2.5 (BLD25) position as predicted by C-MAPSS40K.

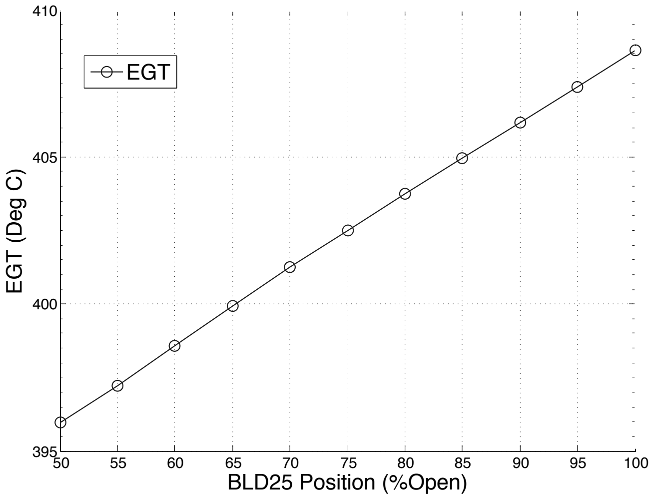

Figure 3. The increase in exhaust gas temperature with air-bleed valve offset.

5. CONCLUSION

The work reported in this paper describes a fault injection apparatus that allows for the creation of precisely controlled fault conditions within the station 2.5 air-bleed valve system of an aircraft integrated turbofan engine. The operator can not only inject a fault in the air-bleed valve system but also control the progression of the fault to a fully failed condition in a nondestructive manner. This will allow an analysis of the engine response signatures which in turn can be used for development of diagnostic and prognostic methods. A simulation of the experiment has shown that multiple engine parameters are indeed perturbed by the valve failure. A lot of emphasis was placed on assuring non-interference with other operation of the aircraft and the engine through a rigorous requirements and engineering process. This required close collaboration with the owners of the engine and the aircraft to assure that all needed operational and procedural rules were followed. To avoid a tedious and costly process for software verification and validation, the entire apparatus was realized through hardware components.

NOMENCLATURE

BOB	Bleed-valve Override Box
$C-MAPSS40K$	Commercial Modular Aero-Propulsion System Simulation
EGT	Exhaust gas temperature
$EHSV$	Electrohydraulic Servo Valve
EPR	Engine Pressure Ratio
$LVDT$	Linear Variable Displacement Transducer
$N1C2$	Temperature corrected low pressure compressor turbine rotational speed
PDM	Prognostic and Decision Making
Wf	Fuel flow rate

REFERENCES

Boyle, D. K. (2014). Preliminary study on acoustic detection of faults experienced by a high-bypass turbofan engine.

Hunter, G. W., Lekki, J., & Simon, D. (2014). Overview of vehicle integrated propulsion research (vipr) testing. In *Meeting abstracts* (pp. 464–464).

Li, Y. (2002). Performance-analysis-based gas turbine diagnostics: A review. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *216*(5), 363–377.

Linke-Diesinger, A. (2008). *Systems of commercial turbofan engines: An introduction to systems functions*. Springer.

May, R. D., Csank, J., Lavelle, T. M., Litt, J. S., & Guo, T.-H. (2010). *A high-fidelity simulation of a generic commercial aircraft engine and controller*. National Aeronautics and Space Administration, Glenn Research Center.

Rinehart, A. W., & Simon, D. L. (2014). An integrated architecture for aircraft engine performance monitoring and fault diagnostics: Engine test results.

Volponi, A. J., DePold, H., Ganguli, R., & Daguang, C. (2003). The use of kalman filter and neural network methodologies in gas turbine performance diagnostics: a comparative study. *Journal of Engineering for Gas Turbines and Power*, *125*(4), 917–924.

BIOGRAPHIES

George E. Gorospe Jr. received the B.E. degree in Mechanical Engineering from the University of New Mexico, Albuquerque, New Mexico, USA, in 2012. Since October 2012, he has been a research engineer at NASA Ames Research Center. In May 2013 he joined Stinger Ghaffarian Technologies and the Prognostic Center of Excellence at NASA Ames Research Center. His current research interests include space mission design, systems engineering, and autonomous mobile robot control and control systems design.

Donald L. Simon is a Controls Engineer at the NASA Glenn Research Center. He holds a B.S. degree from Youngstown State University (1987) and a M.S. degree from Cleveland State University (1990), both in electrical engineering. During his career he has focused on the development of advanced control and health management technologies for current and future aerospace propulsion systems. Mr. Simon's specific research interests are in aircraft gas turbine engine performance diagnostics and performance estimation. He currently leads the propulsion gas path diagnostics effort ongoing under the Vehicle Integrated Propulsion Research (VIPR) effort

Dr. Kai Goebel works at NASA Ames Research Center where he is the Area Lead for Discovery and Systems Health. He received the degree of Diplom-Ingenieur from Technische Universitaet Muenchen in 1990 and the Ph.D. from the University of California at Berkeley in 1996. Dr. Goebel worked at General Electrics Corporate Research Center in upstate New York where he was also an adjunct professor at Rensselear Polytechniq Institute. He has been on the dissertation committee of seven Ph.D. students at RPI, Syracuse University, University of Cincinnati, Vanderbilt University, Georgia Institute of Technology and Stanford University. He is currently guest professor at University of Cincinnati. He holds eighteen patents and he has published more than 300 technical papers.