DEVELOPMENT OF A ROBUST FRAMEWORK FOR CONTROLLING HIGH PERFORMANCE TURBOFAN ENGINES

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To my wonderful wife Tina

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ABSTRACT

This research involves the development of a robust framework for controlling complex and uncertain multivariable systems. Where mathematical modeling is often tedious or inaccurate, the new method uses an extended state observer (ESO) to estimate and cancel dynamic information in real time and dynamically decouple the system. As a result, controller design and tuning become transparent as the number of required model parameters is reduced. Much research has been devoted towards the application of modern multivariable control techniques on aircraft engines. However, few, if any, have been implemented on an operational aircraft, partially due to the difficulty in tuning the controller for satisfactory performance. The new technique is applied to a modern two-spool, high-pressure ratio, low-bypass turbofan with mixed-flow afterburning. A realistic Modular Aero-Propulsion System Simulation (MAPSS) package, developed by NASA, is used to demonstrate the new design process and compare its performance with that of a supplied nominal controller. This approach is expected to reduce gain scheduling over the full operating envelope of the engine and allow a controller to be tuned for engine-to-engine variations.

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NOMENCLATURE

LPC: Low pressure compressor (Booster tip)

HPC: High pressure compressor (Booster hub)

LPT: Low pressure turbine

HPT: High pressure turbine

VABI: Variable-area bypass injectors

MAPSS: Modular aero-propulsion system simulation

GUI: Graphic user interface

CLM: Component level model

Operating Point

pla: Power lever angle

alt: Altitude

xm: Mach number

CLM Actuator Inputs

wf36: Main burner fuel flow

a8: Variable nozzle exit area

a16: Rear bypass door variable area

a14: Forward bypass door variable area *stp2*: Fan inlet guide vane angle

stp27: HPC variable stator vane angle

stp27d: Booster inlet guide vane angle

CLM Sensor Outputs

t3: HPC exit temperature

ps3: HPC exit static pressure

xn2: Fan rotor speed

xn25: Core rotor speed

fn: Net thrust

sm2: Fan stall margin

pcn2r: Percent corrected fan speed

t56: LPT exit temperature

p16qp56: Mixer pressure ratio

ps56: LPT exit static pressure @ mixer

p27: HPC inlet pressure

t27: HPC inlet temperature

Unmeasured Variables

w3: HPC exit mass flow

t4: Burner exit total temperature

Engine States

xn2: Fan rotor speed

xn25: Core rotor speed

tmpc: Average metal temperature across the burner

Performance Parameters

lepr: Liner engine pressure ratio

eprs: Engine pressure ratio

cepr: Core engine pressure ratio

etr: Engine temperature ratio

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CHAPTER I

INTRODUCTION

The jet engine, also known as the gas turbine engine, originated from many different sources. As far back in history as 250 B.C., Heron of Alexandria was said to have built the first reaction engine in a closed sphere with pressurized steam [1]. As illustrated in Figure 1, the steam escaped through two tubes which acted as jet nozzles. This force caused the sphere to rotate on its axis. Rockets made their way into existence in China between the eleventh and thirteenth century A.D. They discovered that a firecracker open at one end would act as a jet nozzle, and when tied to an arrow, it would dart in a straight line.

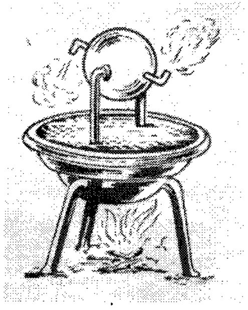

Figure 1: Heron's Reaction Engine

From the mid-1800s to the early 1900s, different engines and airplanes were invented, constructed, and taken into flight. In 1908 Rene Lorin made a revolutionary proposal to compress air with a piston and mix it with fuel. It would then be burned, producing "pulses of hot gases that would be expelled through a nozzle to generate propelling power" [1]. Between the years of 1929 and 1941, two men separately developed engines which would then be used in successful jet-powered aircraft during World War II. Sir Frank Whittle of Great Britain and Han von Ohain of Germany both built and flew their engines: von Ohain's first flight was in 1939 and Whittle's was in 1941 [2].

Since then, jet engine technology has advanced to the point of being considered one of the most complex systems in existence. Chapter II gives a brief introduction to the different types of jet engines and the progression of their mathematical models. A simulation package of a modern low bypass turbofan with a fully functional digital controller was developed in cooperation with NASA. Part of this research included completely rewriting its interface to automate the testing of new controllers. This amounted to over 3000 new lines of code. Functionality was also added to create, simulate, and compare of 27 different types of linear models proposed in [3]. Details of the supplied multi-mode digital controller are then given. The primary objective of control is to maintain a level performance within safe operating limits of the engine.

Improvements to control algorithms promise a high return on investment with little or no hardware modification. Chapter III outlines several model based control methods that have been proposed, yet none have ever been implemented because of the inability to adjust the controller for peak performance on an actual aircraft. Multivariable proportional-integral-derivative (PID) controllers are currently used in practice, but they require the complex adjustment of several parameters. This manual adjustment of controller parameters is referred to as tuning. A deeper look at current control structures for complex multivariable systems in general uncovers a few inherent problems. As a result, several new disturbance rejection and error based control methods are investigated. A technique referred to as Active Disturbance Rejection Control (ADRC) appears to be a practical solution because it provides high performance through a simple design procedure.

Chapter IV proposes a new framework for controlling complex and uncertain systems. A discrete implementation and generalization of the extended state observer (ESO) is first proposed to improve the performance of ADRC. Based on ADRC concepts, a new two degree-of-freedom (DOF) control structure, referred to as generalized PID (GPID), is then proposed. Finally, both ADRC and GPID are extended to control multiple-input multiple-output (MIMO) systems of arbitrary order. A gain and order estimation method is also proposed.

Multivariable ADRC is applied to the jet engine in Chapter V. The new algorithm is simulated at a few operating points and the results are discussed. Concluding remarks, given in Chapter VI, include future research directions as a direct result of this work.

CHAPTER II

PROBLEM FORMULATION

This chapter begins with a brief introduction of jet engines, focusing on the low bypass turbofan. Different models are then presented, followed by a discussion of control objectives, performance specifications, and engine limits. The details of the nominal engine controller are also given.

2.1 Types of Jet Engines

Before there were jet engines on aircraft, a piston engine was used to turn a propeller. The propeller would produce a small acceleration on a relatively large mass of air. Conversely, the gas turbine engine produces a relatively large acceleration directly on a small mass of air [1]. This design allows for quieter operation, better efficiency, and produces much more thrust for a given engine weight. The simplest gas turbine engine is the turbojet. The cylindrical engine case houses an axial compressor, burner, and turbine. The ambient air entering the engine is first compressed by the multi-stage compressor, mixed with fuel, and combusted in the burner section to produce thrust. Roughly seventy-five percent of the thrust produced is consumed by the multi-stage turbine, which rotates the compressor through a common shaft [1]. The compressor-shaft-turbine combination is called a spool. The remaining twenty-five percent of the thrust exits through the rear nozzle to propel the aircraft.

There are many variations to the basic turbojet design, formed by combining the concepts of the twin-spool turbojet, turboprop, high and low bypass turbofan, and afterburner concepts. When an engine is comprised of two spools, the incoming air passes through a low pressure compressor (LPC) and a high pressure compressor (HPC) before it is mixed with fuel and combusted. The thrust produced is absorbed first by a low pressure turbine (LPT), and then by a high pressure turbine (HPT) before the remaining thrust exits through the rear nozzle. The dual-rotor design improves compressibility mismatch across the compressor, the key component affecting performance [2]. The LPC and HPC rotors, functioning as a unit, greatly improve efficiency at off-design operating points while achieving higher pressure ratios. The design of variable inlet stator guide vanes has also significantly improves compressor performance. The combination of the HPC, combustor, and HPT is commonly referred to as the engine core. The turboprop has a propeller that is connected to the low pressure spool shaft through a gearbox.

The turbofan engine is a jet engine with a bypass stream. In this configuration, a large fan is diametrically attached to the front compressor stage or stages allowing a portion of the air to bypass the engine core and directly produce thrust. Although similar in concept to the turboprop, the bypass duct is designed so that the flow passing through it is not affected by the vehicle's airspeed. The ratio between the secondary bypass air stream and the primary air stream flowing through the engine core is called the bypass ratio. In general there are two basic types of turbofan engines; high-bypass turbofan engines, shown in Figure 2 which are typical of commercial and transport aircraft, and low-bypass military jet engines.

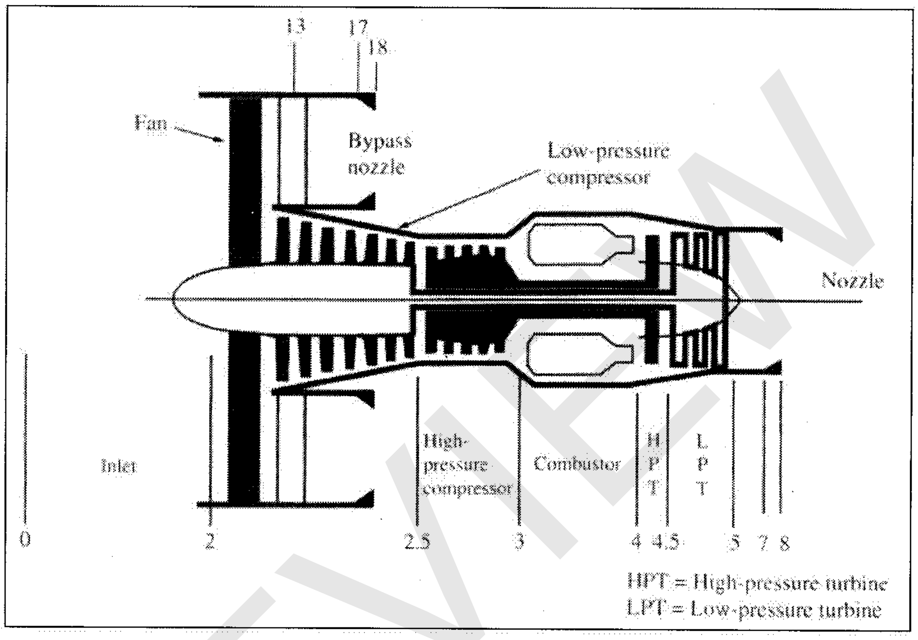

Figure 2: Schematic of a High-Bypass Turbofan

The afterburner, characteristic of military or high speed aircraft, is a long cylindrical section positioned between the rear turbines and the exhaust nozzle of the jet engine. Here the exhaust gases are mixed with fuel and re-combusted to thoroughly burn any un-combusted products. When implemented on a turbofan, it is not uncommon for the bypass stream to be mixed with the core stream through variable area bypass injectors (VABI) before entering the afterburner. This is referred to as mixed-flow afterburning. The exhaust nozzles have variable geometry to minimize the backlash of the reheat operation [4]. A schematic is shown in Figure 3 with labeled actuators (top) and sensors (bottom) [5].

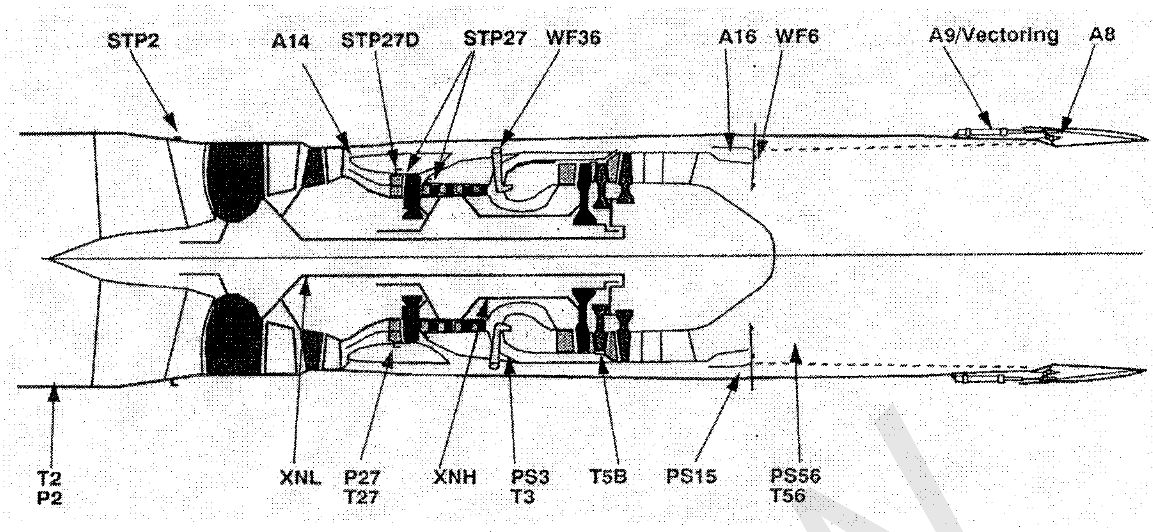

Figure 3: Schematic of a Low-Bypass Turbofan with Afterburner

2.2 Modular Aero-Propulsion System Simulation

Recently, the NASA Glenn Research Center has developed a Modular Aero-Propulsion System Simulation (MAPSS) package in Simulink® that incorporates a working military jet engine and a digital controller [6]. Both are completely configurable through a Graphic User Interface (GUI), allowing easy access to any signal in the engine or controller. This non real time multi-rate package is freely-distributed and will serve as a basis for simulation and controller design.

The engine used in MAPSS is a two-spool, high pressure ratio, low bypass turbofan with mixed-flow afterburning, similar to that in Figure 3. A multi-stage fan provides initial compression followed by a multi-stage HPC. An annular combustor, situated between the compressor and turbine stages, increases the energy state of the core gases to provide adequate fan and compressor energy requirements as well as sufficient thrust for the aircraft [7]. These gases are then expanded through high and low pressure turbines which drive the compressor and fan, respectively. The exhaust gases are mixed with the bypass stream through adjustable forward and rear VABI which regulate the bypass ratio to suit the overall cycle demands. For additional thrust on demand, more fuel is mixed with the turbine exhaust and re-combusted in the afterburner. The exhaust nozzle is equipped with variable convergent-divergent areas to provide controlled expansion of the exhaust gases to ambient pressure while maintaining proper back pressure to the engine [7]. Although other engines may vary slightly from this configuration, the concepts discussed here can be extended with minimal effort.

The MAPSS GUI, shown in Figure 4, provides a way for the designer to run the jet engine through various operating points, change engine constants including health parameters, plot any signal of interest, and save and compare the results. It was completely rewritten to automate the process of simulation and testing of new control laws. The GUI also automatically loads and saves initial conditions for the model and allows the user to setup several simulation runs at one time, allowing them to run sequentially and unattended over night. A built-in function allows the designer to create linear models for several operating points at once, run them in place of the full engine model, and compare the results with that of the corresponding nonlinear simulation.