

Multivariable Aircraft Engine Controller Design Using an Optimal Loop Shaping Approach

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ABSTRACT

The current pressure for fuel burn savings and increasing performance in the commercial aerospace market demands highly complex engine control systems to optimize fuel consumption throughout the engine operating envelope, as well as meet the regulatory requirements in terms of safety and performance. These conflicting objectives normally lead to trade-off solutions that are difficult to precisely estimate. Therefore some decisions to characterize the engine controller still reside on experience from previous designs and, as a result, add subjectivity and increase the potential for wrong parameter selection.

This paper proposes an algorithmic approach to design a turbojet engine controller in a multivariable, two-degree-of-freedom configuration, obtaining H-infinity robust stabilization. It introduces an optimized loop shaping design procedure, with the use of a Genetic Algorithm (GA), to further improve the control system performance, as well as bring the experience applied by controller designers and engineers to an automated process, when setting the parameters to shape the frequency response of the engine control loops. The resulting controller is evaluated by computer simulations under typical operating conditions and it is compared to other strategies like a discrete-time Linear Quadratic Regulator with Integral Action (LQI) as well as a Linear Quadratic Gaussian (LQG) controller with Loop Transfer Recovery (LTR).

H-infinity controller presented a satisfactory behavior with smoother responses than the other controllers, however with higher rise times; control devices for the subject controller presented the best transient response among all others and indicated a positive impact in the fuel consumption. Finally, a noise immunity check revealed that this H-infinity controller

was capable to properly attenuate high frequency noise normally present in the measurement systems.

INTRODUCTION

While aviation market demands engine optimization in order to provide the required level of thrust or power for a given mission with minimal costs, safety standards for this market segment pursue robust engines that would show satisfactory operating characteristics when exposed to a variety of environmental conditions. These conflicting objectives point to the need of very complex systems to deal with several variables and require a significant amount of processing effort to determine the control action to be taken in each iteration ([Subbu et al., 2005](#)).

Digital computers have extraordinarily evolved in the recent years in a way that they allow control system designers to add complexity to the controllers; however the high number of variables normally determines numerous simulations in the development phase of the engine controller. Time constraints and limited resources are also factors that prevent an optimal solution to be reached in most of the cases.

Therefore, empirical knowledge brought by experience with previous controllers for gas turbine engines is essential to the success of the design. In an effort to bring this experience to the gas turbine engine control design, the authors propose to combine robust stabilization and algorithmic design with the use of Genetic Algorithm (GA), to determine some parameter selection during the design process. The controller structure was chosen to be an adapted version of a two-degree-of-freedom controller, with H_∞ robust stabilization and loop shaping approach as presented by [Skogestad and Postlethwaite \(2005b\)](#). Focus was given in the loop shaping design procedure, where the determination of the weight functions of the frequency response for sensibility and

complementary sensibility functions significantly influence the resulting controller.

DEVELOPMENT

In this section, the engine model is described along with all steps taken to obtain the proposed controller. The following subsections help organizing the development and represent the relevant processes.

THE ENGINE MODEL

The selected aircraft engine to conduct this investigation is the Rolls Royce's Spey™, which model was widely explored by Skogestad and Postlethwaite (2005b) to produce robust multivariable controllers. Much of this paper is based on the work they developed.

This engine is a small turbofan with a low bypass ratio (about 0.64:1) installed on modern military aircraft. A cross section of this turbofan is shown in Fig. 1. It is comprised of a core shaft called high pressure (HP) shaft that contains the turbine that drives the engine compressor, by transforming part of the energy released by the fuel combustion into mechanical energy to compress the air that flows through the engine. Another turbine is then attached to a second shaft, called low pressure (LP) shaft, which will expand the remaining gases from the HP turbine to drive the engine LP compressor at the inlet. Among the aircraft that have this engine installed in are EMBRAER's AMX, MD's F-4B Phantom II, Gulfstream's GII and later variants of the Blackburn's Buccaneer.

Three control signals are used for engine operation: 1 - WFE: Weighted Fuel Flow, controlled by a fuel metering valve; 2 - AJ: Exhaust Nozzle Area, controlled by an actuator; and 3 - IGV: LP Compressor Vanes Angle, also controlled by an actuator.

For the development of the robust controller, a linear model of this engine was used in the state-space format (Skogestad and Postlethwaite, 2005a). It comprises 18 states and 6 outputs, however this model was reduced to 3 outputs: 1 - OPR1: Pressure ratio between the HP compressor outlet and the LP compressor inlet [unitless]; 2 - LPEMN: Air flow velocity at the exit of LP compressor [Mach number]; and 3 - NH: HP shaft rotation [percentage of max rpm]. This reduction was done due to the fact that the control devices would have a more direct effect over these outputs, but also to simplify it to handle multiple simulations in a timely manner. It is important to mention that the variable exhaust nozzle area (AJ) control device was available only in some variants of this engine.

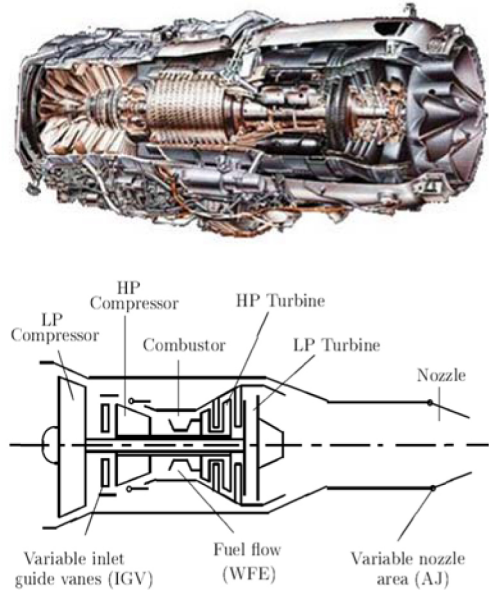


Figure 1. Cross Section of Spey™ from Rolls Royce
(Skogestad and Postlethwaite, 2005b)

These three outputs were selected and ordered to reduce the coupling effect between cross input-output relations, through a Relative Gain Array (RGA) analysis (Bristol, 1966), where the relative impact of the inputs on the outputs are measured providing a tool for the control system designer in order to properly pair inputs to outputs in the system. From now on, the abovementioned order will be respected whenever combined input-output plots are presented.

PERFORMANCE AND STABILITY ANALYSIS OF THE ENGINE MODEL

Nominal Stability (NS) can be initially assessed through an analysis of the poles of the engine model, listed in Tab. 1. All the poles are located in the left-half plane of s-domain thus the engine model is nominally stable.

For completeness, Tab. 1(b) lists the zeros of the model. There could be potential issues with frequency bandwidth limitation since there are some zeros in the right-half plane (Kinnaert, 1990). However these zeros are far away from the imaginary axis as well as from the desired bandwidth of 10 rad/s, thus the impact on the bandwidth is not of a major concern in this project.

Nominal Performance (NP) can be assessed in the frequency domain through the condition number analysis, which quantifies the level of correlation between inputs and outputs in MIMO (Multiple Inputs and Multiple Outputs) systems. It is defined, as expressed in Eq. (1), as the ratio between the maximum and the minimum singular values.

$$\gamma(\mathbf{G}) = \frac{\bar{\sigma}(\mathbf{G})}{\underline{\sigma}(\mathbf{G})} \quad (1)$$

where $\mathbf{G}(s)$ is the transfer function between engine model inputs and outputs. Additionally, an important measure of gain direction is given by a factorization of $\mathbf{G}$ in a determined frequency, called Singular Value Decomposition (SVD). Condition number and the singular values in the frequency of the engine model are shown in Fig. 2. Analysis of the condition number points out that large values may represent issues for controllers that invert the model dynamics, however Fig. 2(b) shows that condition number is small through the desired bandwidth.

Table 1. Poles and Zeros of the Engine Model

Real	Imaginary	Real	Imaginary
-96.90595	± 270.89	-40.13364	± 185.0046
-245.0538	± 26.12624	-103.2232	± 114.4215
-87.8816	± 29.4027	-1.3309	0
-327.2601	0	-5.0877	0
-31.25 ⁽¹⁾	0	-31.25 ⁽²⁾	0
-44.10	0	-62.5 ⁽³⁾	0
-158.5943	0	-	-

(a) Poles of the linear engine model

⁽¹⁾: Characteristic Pole of Fuel Metering Valve

⁽²⁾: Characteristic Pole of Exhaust Nozzle Actuator

⁽³⁾: Characteristic Pole of IGV Actuator

Real	Imaginary	Real	Imaginary
-57.79707	± 231.5439	-202.4119	± 171.9277
-12.7264	0	-48.9355	0
-167.2313	0	-265.0553	0
-91.1695	0	46881.6057	0
842758.6547	0	-	-
-	-	-	-
-	-	-	-

(b) Zeros of the linear engine model

Time domain performance was investigated by analysis of the unit step input responses. It is important to mention that this engine model is scaled so that each variation of 7.5% of maximum thrust represents a unit variation of OPR1; each unit variation of LPEMN is followed by 5% change in the surge margin of the LP compressor; and a unit variation of NH corresponds to 2.2% of the maximum rotation of the HP shaft.

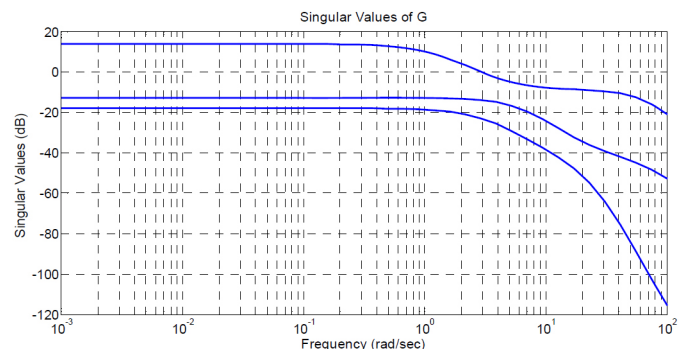
Although responses are stable, nominal performance needs improvements: the cross-coupling effect is exacerbated in the NH response to the WFE input, steady state error is present in

most of the responses and rise times are higher than typical for this class of turbojets.

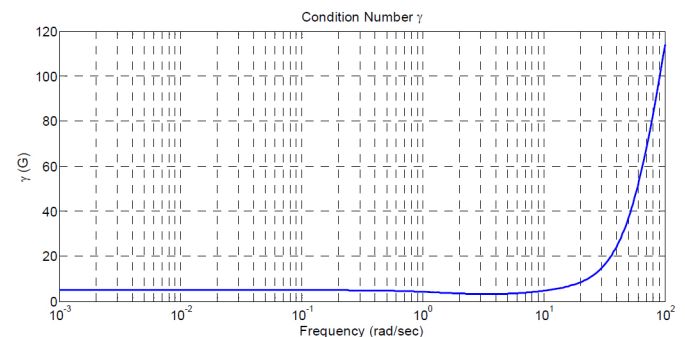
In order to effectively improve the performance of this engine, a robust controller was designed with the use of the H_∞ robust stabilization with Loop Shape Design Procedure (LSDP) and 2 degrees of freedom (2DOF). The robust stabilization design will ensure the controller is capable of controlling the engine even when the engine response presents small variations from the engine model, while the LSDP is a method that shapes the open loop response of the system by adding pre and post-compensators in cascade with the engine model. Next section will focus on the controller design development and these concepts will be explored in more details.

2DOF H_∞ CONTROLLER WITH LSDP

The objective of the 2DOF H_∞ controller is to minimize the tracking error from the reference inputs as well as to be robust enough to accommodate variations of the real engine behavior from the engine model, which may be caused by unknown uncertainties in the model or even by external disturbances. A methodology to develop this type of controller (Skogestad and Postlethwaite, 2005b) is described in the following sections.



(a). Singular Values Decomposition of G



(b). Condition number evolution

Figure 2. Singular Values Decomposition and Condition Number Evolution (Skogestad and Postlethwaite, 2005b)

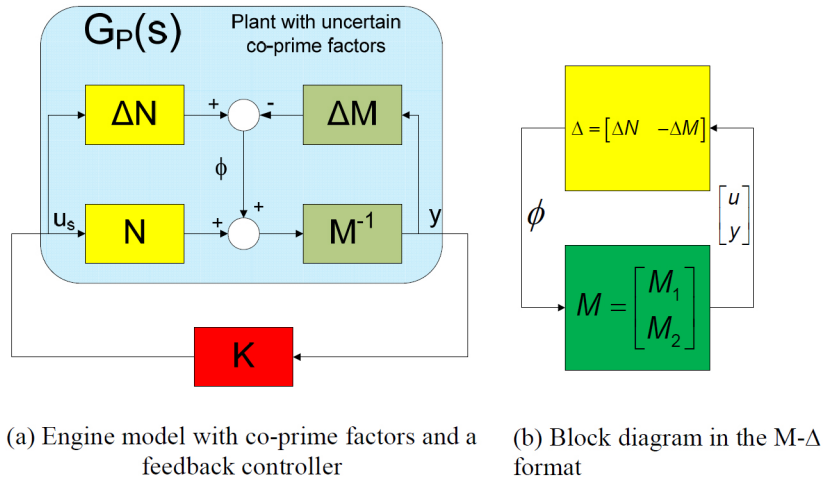


Figure 3. Engine System Configurations

Project Overview

Complex systems such as aircraft engines have a large number of states and call for very complex models. In addition, actual operation is surrounded by disturbances, like sensors noise, manufacturing tolerances of the engine components, as well as variations of the environmental conditions. Due to the nature of these disturbances, it poses a big challenge to model them or at least encapsulate them to a known envelope. Therefore some assumptions are necessary to simplify the model to a level that it can be handled by the control system engineer, as well as present representative characteristics around the conditions of the normal operation. One alternative approach, used by Gu et al. (2005), is to define the model as a function of co-prime factors as illustrated in Fig. 3(a). Equations 2 and 3 are extracted from that block diagram.

$$\mathbf{G}(s) = \mathbf{M}^{-1} \cdot \mathbf{N} \quad (2)$$

$$\mathbf{G}_p(s) = (\mathbf{M} + \Delta \mathbf{M})^{-1} \cdot (\mathbf{N} + \Delta \mathbf{N}) \quad (3)$$

$\mathbf{M}^{-1}$ and $\mathbf{N}$ are the engine's model coprime factors and $\Delta \mathbf{M}$ and $\Delta \mathbf{N}$ are their respective uncertainties block.

Variations of the engine from its model can now be represented as unknown uncertainties to the coprime factors. Therefore a measure of the system robustness can be defined as an amount of the deviation from the model that would still provide a stable response to its inputs. Consider the following family of stable models, defined in Eq. 4.

$$\mathbf{G}_p(s) = \left\{ (\mathbf{M} + \Delta \mathbf{M})^{-1} \cdot (\mathbf{N} + \Delta \mathbf{N}) : \left\| \begin{bmatrix} \Delta \mathbf{N} & \Delta \mathbf{M} \end{bmatrix} \right\|_{\infty} \leq \right\} \quad (4)$$

$\|\cdot\|_{\infty}$ is the infinite norm operator and is called the stability margin. In this project the objective is to maximize this margin so that the engine system is as robust as possible, however considering the restrictions to the control device physical limitations such as detents and rate limits. This margin is increased with the help from a feedback controller, which representation can be seen in Fig. 3(a) and Fig. 3(b).

The H_{∞} Controller Synthesis is a method to determine the controller $\mathbf{K}$ that would maximize the stability margin. There will be a specific subsection to better explain the robust stabilization process for the controller design. For now, it is important to emphasize that this method aims at robustness; however performance aspects like reference tracking and rise times are not directly addressed. The alternative for this issue was to include a second element for the controller, or a second degree of freedom, so that the tracking performance could be added and considered in the design. Additionally, a loop shape design as well as a reference model ($\mathbf{T}_{\text{REF}}$) were also included in order to produce smooth set point curves and let the engine respond without abrupt commands from the control devices. Error and reference scaling factor ρ is added to adjust the emphasis of the design between robustness and accuracy. The complete system is presented in Fig. 4(a), where $\mathbf{G}_{ps}(s)$ is defined as the family of open loop models, after the loop shape design is incorporated to the model. $\mathbf{K}_1$ is the element of the controller responsible for reference tracking while $\mathbf{K}_2$ takes care of the system's internal stability.

Open Loop Shape Design

In the previous subsection, the complete engine system was described with its controller components. The complexity of both the structure of this controller and of the engine model makes the system design a big challenge, specially the task of tuning the adjustable parameters. Another important factor to succeed in this type of design is to bring the open loop shaped