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Multivariable Real-time Decoupling Control of Aviation Turbofan Engines

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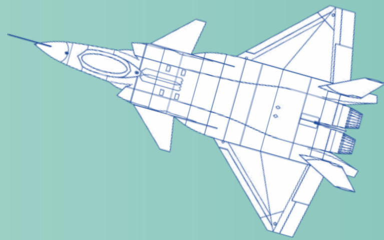

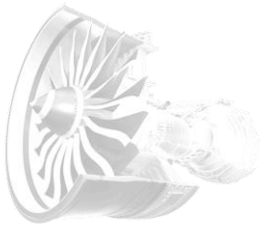

Content

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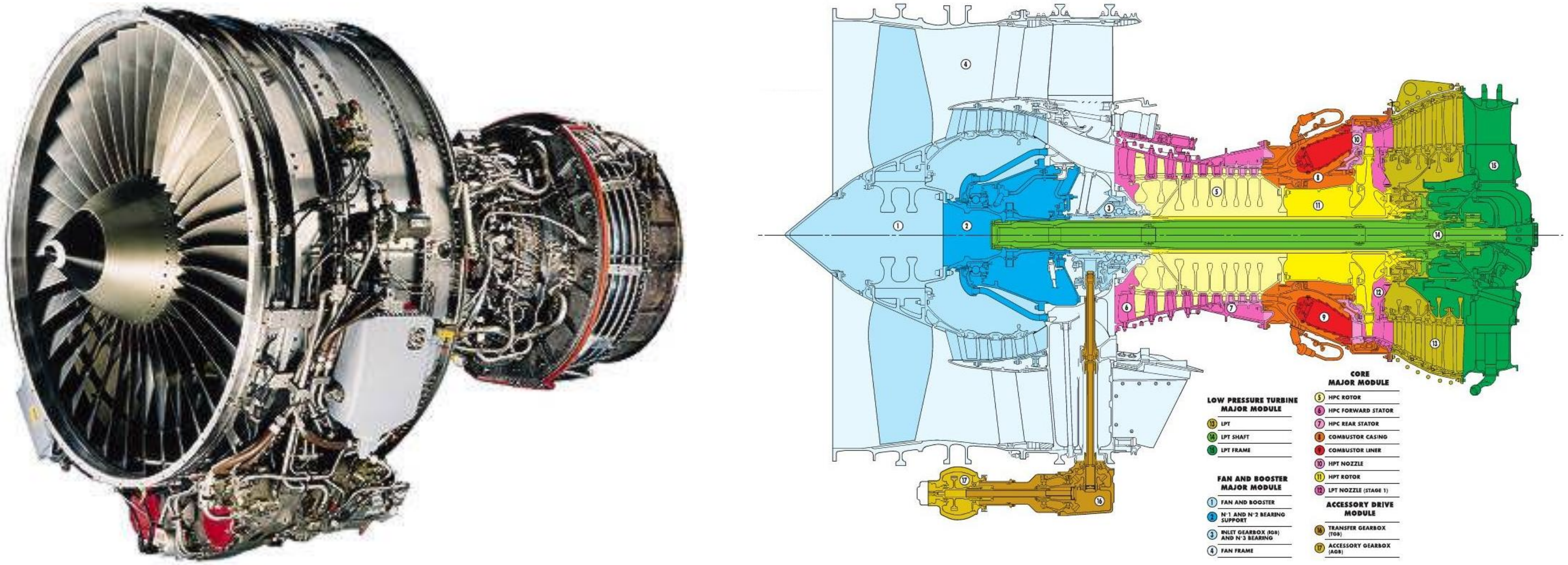
PART ONE

Introduction

I. Introduction

- *The gas turbine engine (GTE) is one of the most complex machines ever built, not only for its constructive intricacies, but also for the dynamic behaviors it displays and the sophisticated engineering required for its operation.*



Schematic diagram of a commercial aero-engine, one kind of GTE

I. Introduction

- *Gas turbine engines must be operated by means of control, and how to achieve multivariable control decoupling under the premise of satisfying their operating constraints, while achieving the optimal performance of aero-engine is an open thorny issue attracting increasingly more attention.*
- *By the idea of inverse system, a novel control structure and fully combines multivariable decoupling control with performance seeking control is proposed in this paper. Subsequently, A multivariable dynamic decoupling in the form of pseudo linear system is realized and aero-engine potential is fully exploited utilizing performance seeking.*

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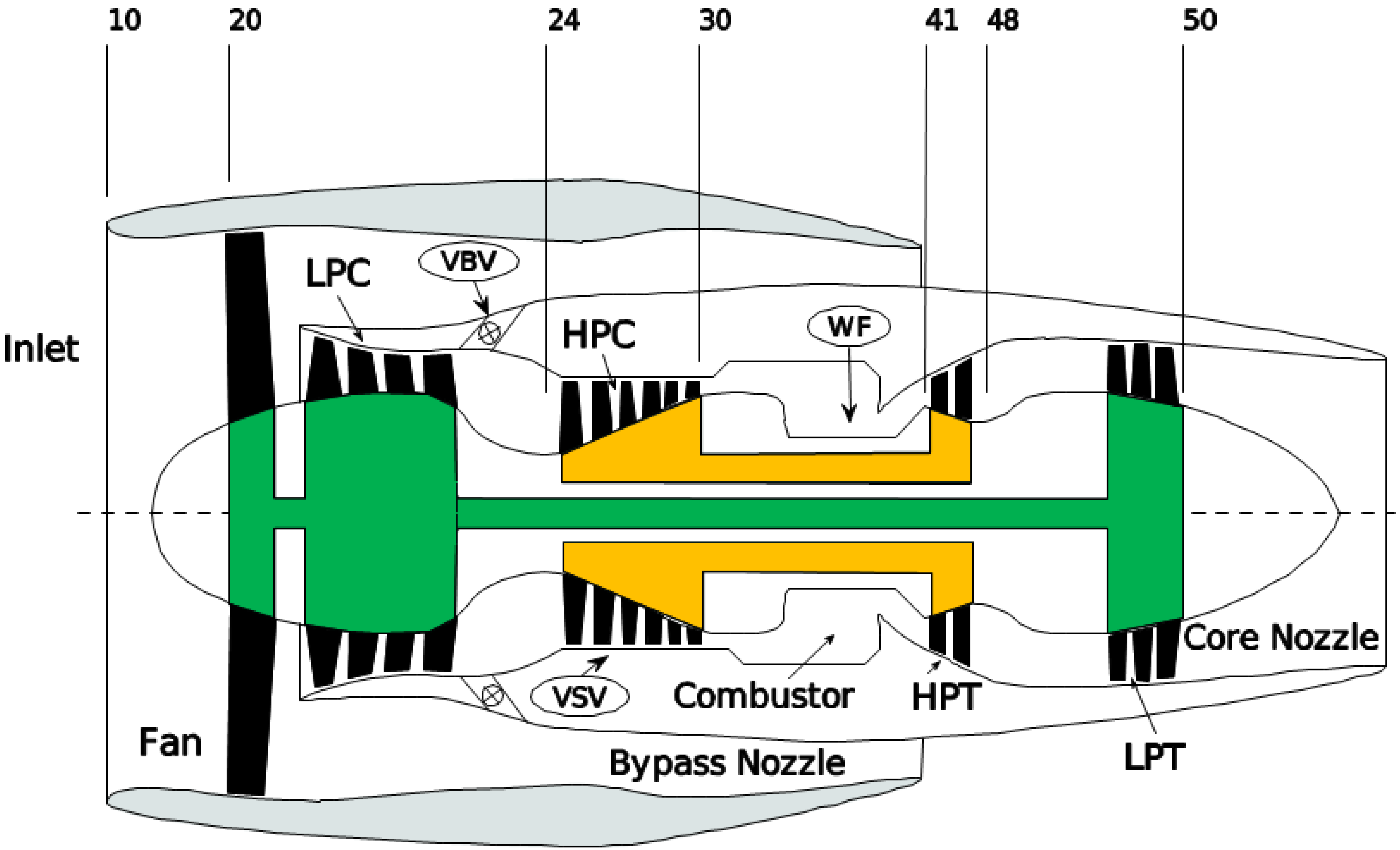
PART TWO

Turbofan Engine and Its Model

II. Turbofan Engine and Its Model



Structural representation of two-spool commercial turbofan engine

II. Turbofan Engine and Its Model

- *Figure above illustrates the two-spool turbofan engine upon which this paper is based. The fan, low-pressure compressor (LPC) and low-pressure turbine (LPT) are connected by one shaft and thus rotate synchronously. The high-pressure compressor (HPC) and high-pressure turbine (HPT) are next to the combustor and are connected by a separate shaft, usually concentric with the LP shaft. The arrangement of HPC, combustor, HPT, and core nozzle is referred to as core engine. The symbols WF, VBV, and VSV enclosed in ovals correspond to the main actuators used in GTE control systems. WF corresponds to the fuel flow delivered by a pump. VBV denotes the variable bleed valve. VSV represents the variable stator vanes.*

II. Turbofan Engine and Its Model

- *This section offers a brief overview of engine dynamics, aiming at the extraction of linearized models that can be used as a basis for linear parameter-varying (LPV) model and control design. The nonlinear model of engine dynamics is as follows:*

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{\eta}) \\ \boldsymbol{y} = \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{\eta}) \end{cases} \tag{1}$$

- *where* $\boldsymbol{x} = [N_f, N_c]^T$ *is state vector,* $\boldsymbol{u} = [WF, VSV, VBV]^T$ *is control input vector,* $\boldsymbol{y} = [N_f, N_c, T_{48}, SM_{\mathrm{HPC}}, \ldots]^T$ *is output vector and* η *contains the health parameters, a set of quantities representing engine deterioration and faults.* $\boldsymbol{f}$ *and* $\boldsymbol{g}$ *are state and output function vectors respectively.*

II. Turbofan Engine and Its Model

- *At a steady-state operating point of engine, small-signal linearization of Eq.(1) is performed and high order terms is omitted, yielding the model*

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}_0, \boldsymbol{u}_0, \boldsymbol{\eta}_0) + \left.\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}^T}\right|_0 (\boldsymbol{x} - \boldsymbol{x}_0) + \left.\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{u}^T}\right|_0 (\boldsymbol{u} - \boldsymbol{u}_0) + \left.\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{\eta}^T}\right|_0 (\boldsymbol{\eta} - \boldsymbol{\eta}_0) \\ \boldsymbol{y} = \boldsymbol{g}(\boldsymbol{x}_0, \boldsymbol{u}_0, \boldsymbol{\eta}_0) + \left.\frac{\partial \boldsymbol{g}}{\partial \boldsymbol{x}^T}\right|_0 (\boldsymbol{x} - \boldsymbol{x}_0) + \left.\frac{\partial \boldsymbol{g}}{\partial \boldsymbol{u}^T}\right|_0 (\boldsymbol{u} - \boldsymbol{u}_0) + \left.\frac{\partial \boldsymbol{g}}{\partial \boldsymbol{\eta}^T}\right|_0 (\boldsymbol{\eta} - \boldsymbol{\eta}_0) \end{cases} \tag{2}$$

- *where the subscript 0 has been used to indicate that the partial derivatives are evaluated at steady-state conditions. Simplify (2) to get the state-space form*

$$\begin{cases} \Delta\dot{x} = \boldsymbol{A}\Delta x + \boldsymbol{B}\Delta u + \boldsymbol{L}\Delta\eta \\ \Delta y = \boldsymbol{C}\Delta x + \boldsymbol{D}\Delta u + \boldsymbol{M}\Delta\eta \end{cases} \tag{3}$$

II. Turbofan Engine and Its Model

- *For a nonlinear system in (1), the set of equilibrium points or steady-state points*

$$\boldsymbol{\Gamma}_e := \{(\boldsymbol{x}_0, \boldsymbol{u}_0, \boldsymbol{\eta}_0) | \boldsymbol{f}(\boldsymbol{x}_0, \boldsymbol{u}_0, \boldsymbol{\eta}_0) = 0,\ \boldsymbol{y}_0 = \boldsymbol{g}(\boldsymbol{x}_0, \boldsymbol{u}_0, \boldsymbol{\eta}_0)\}$$

- *Select N equilibrium points at the typical operating point*

$$\boldsymbol{\Gamma}'_e := \{(\boldsymbol{x}_{i,0}, \boldsymbol{u}_{i,0}, \boldsymbol{\eta}_{i,0}) | \boldsymbol{f}(\boldsymbol{x}_{i,0}, \boldsymbol{u}_{i,0}, \boldsymbol{\eta}_{i,0}) = 0,\ i \in \{1, \ldots, N\}\}$$

- *The scheduling variable* $\boldsymbol{p}(t)$ *is selected as the state vector* $\mathfrak{x}$

II. Turbofan Engine and Its Model

- *Parameterize the coefficient matrices* $(\boldsymbol{A},\boldsymbol{B},\boldsymbol{C},\boldsymbol{D})$ *and equilibrium points* $\boldsymbol{\Gamma}'_e$ *with the weighted sum similar to RBF neural network, the model in (3) can be written as the LPV form*

$$\begin{cases} \dot{\boldsymbol{x}} = \dot{\boldsymbol{x}}_0(\boldsymbol{p}) + \boldsymbol{A}(\boldsymbol{p})[\boldsymbol{x} - \boldsymbol{x}_0(\boldsymbol{p})] + \boldsymbol{B}(\boldsymbol{p})[\boldsymbol{u} - \boldsymbol{u}_0(\boldsymbol{p})] \\ \boldsymbol{y} = \boldsymbol{y}_0(\boldsymbol{p}) + \boldsymbol{C}(\boldsymbol{p})[\boldsymbol{x} - \boldsymbol{x}_0(\boldsymbol{p})] + \boldsymbol{D}(\boldsymbol{p})[\boldsymbol{u} - \boldsymbol{u}_0(\boldsymbol{p})] \end{cases}$$

- *for example:*

$$\boldsymbol{A}(\boldsymbol{x}) = \frac{\sum_{i=1}^{N}[w_i(\boldsymbol{x})\boldsymbol{A}_i(\boldsymbol{x}_{i,0})]}{\sum_{i=1}^{N} w_i(\boldsymbol{x})} \qquad w_i(\boldsymbol{x}) = e^{-\beta_i \frac{\left\|\boldsymbol{x}-\boldsymbol{x}_{i,0}\right\|^2}{\sigma^2}}$$

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PART THREE

Multivariable Dynamic Decoupling Control

Ⅲ. Multivariable Dynamic Decoupling Control

➢ *A. Nonlinear Dynamic Inverse*

- *The basic idea: for a given system, firstly, an α-order integral inverse system is generated for the original system by using the model of controlled system, to compensate the original system into a linear transfer relationship and decoupled normalization called a pseudo-linear system; then the various design theories of linear system can be used to complete the synthesis of the pseudo-linear system. So the inverse system method is an effective and efficient pre-processing decoupling method.*
- *For the physical system of aero-engine, the numerator of the transfer function is one order lower than its denominator. Therefore, the engine's first-order integral inverse system is applied herein.*

Ⅲ. Multivariable Dynamic Decoupling Control

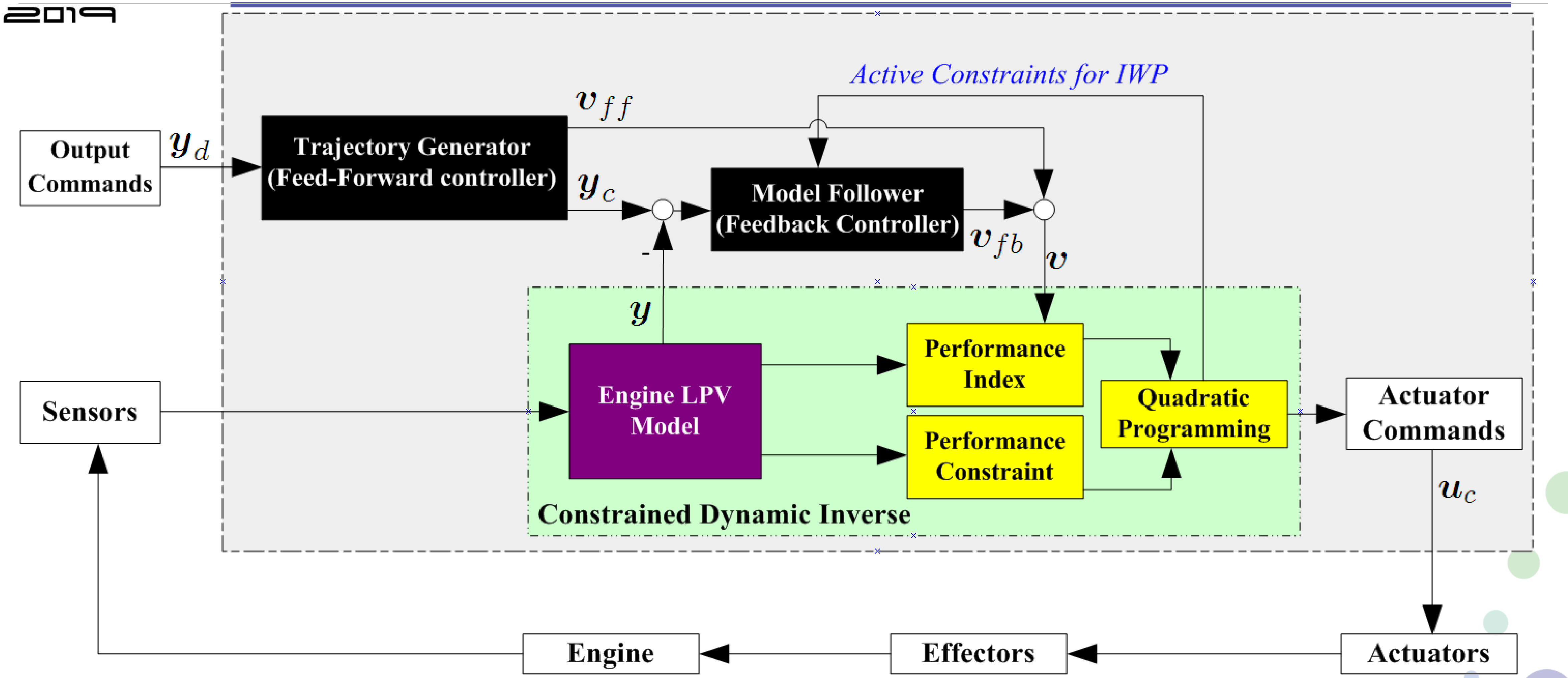
B. Constrained Optimization

- *In a relatively short control period, using the local linear model of aero-engine to construct a convex programming, the solution to the constrained optimization problem can usually be solved real-time.*

C. Multivariable Decoupling and Dynamic Performance Seeking Control

- *In a sense, the controller design is more or less a search for inverse of the original controlled system, and the purpose of control is to meet some standards, usually the optimal or sub-optimal of some goals. The optimal control is to find the appropriate control in the constrained control domain in order to achieve some goals optimization.*

Ⅲ. Multivariable Dynamic Decoupling Control



Logic architecture of multivariable dynamic performance seeking control for engine

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PART FOUR

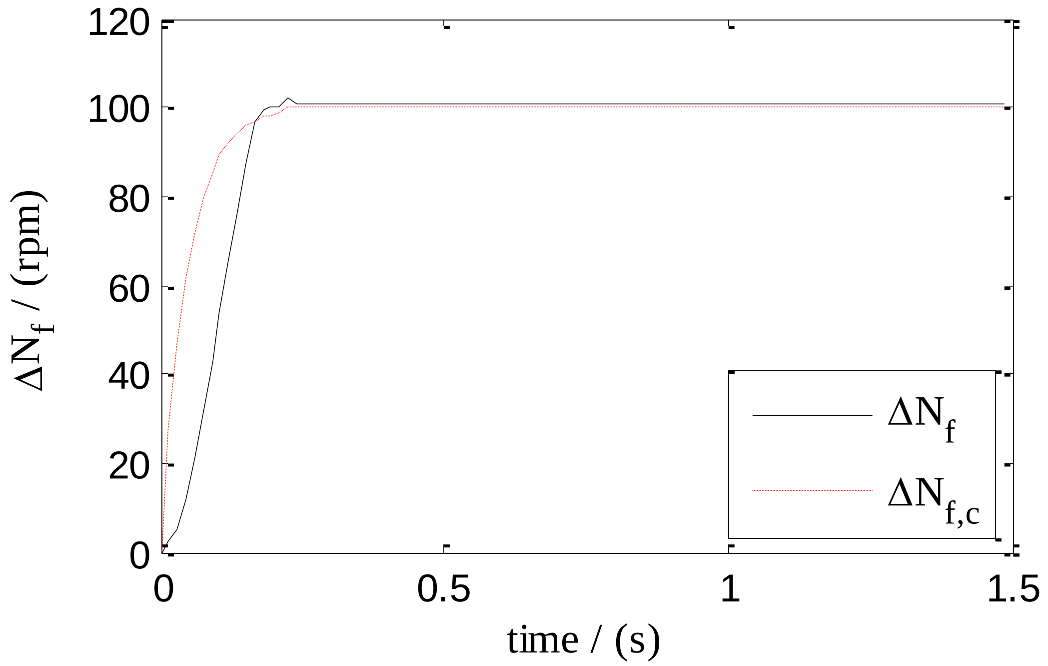
Simulation and Analysis

IV. Simulation and Analysis

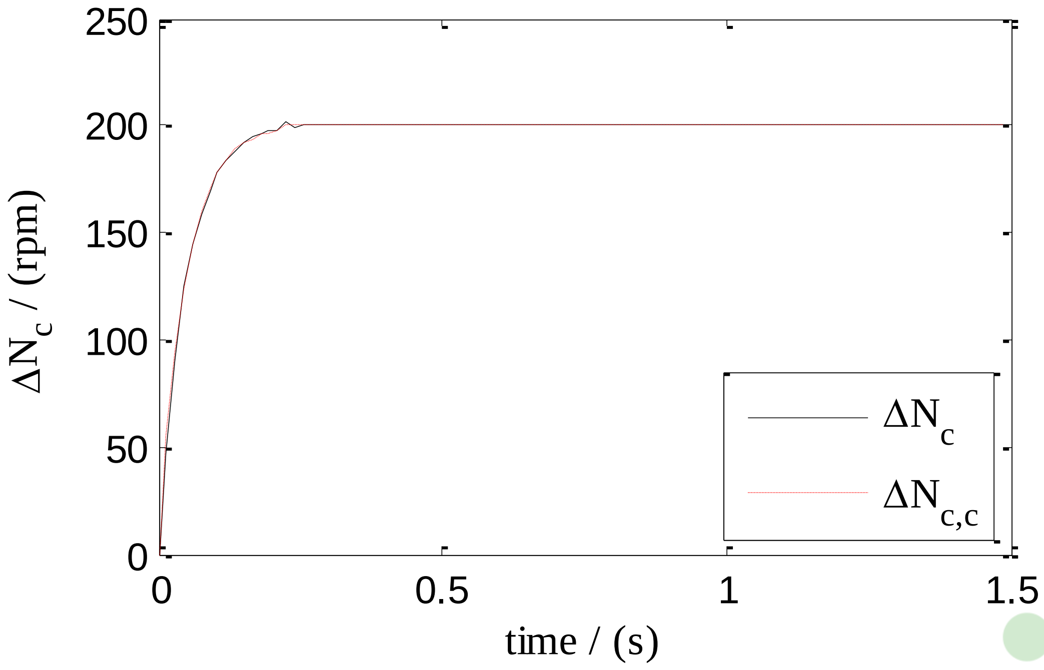
- *A simulation is now conducted using the nonlinear model of a commercial turbofan engine. The multivariable decoupling and dynamic performance seeking control schemed is tested under a large transient process starting with a steady state of engine.*
- *It can be seen from the simulation results that the tracking errors of both* N_f *and* N_c *are small, meaning that the decoupling effect between the two control loops is good, and the input and output are all varied within the limit range. It should be noted that in the initial stage of the engine transient process, VBV reaching limit leads to the dynamic tracking error in* N_f*, which also discloses from another perspective that not all control goals can be satisfied when one or more controls reach the limit.*

IV. Simulation and Analysis

The relative change from the initial steady state point

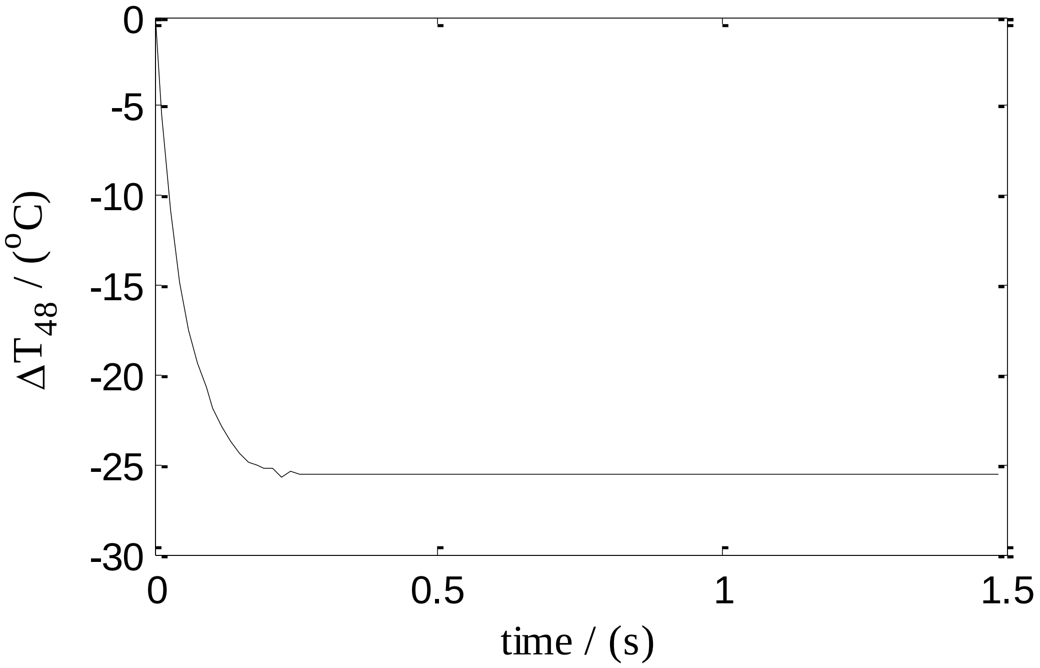


fan speed

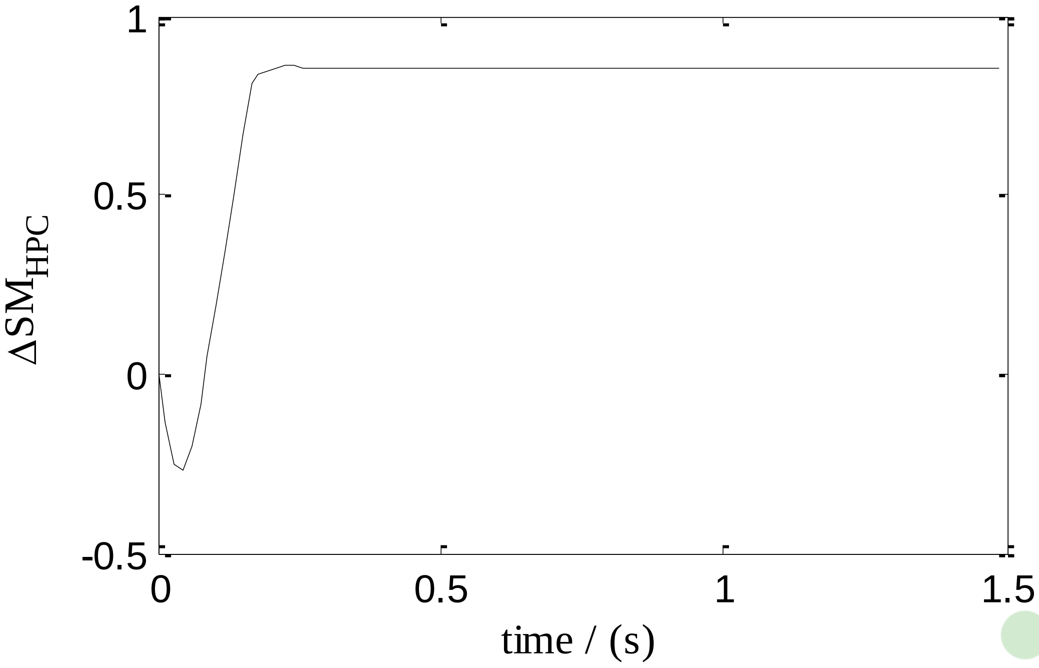


core speed

Ⅳ. Simulation and Analysis

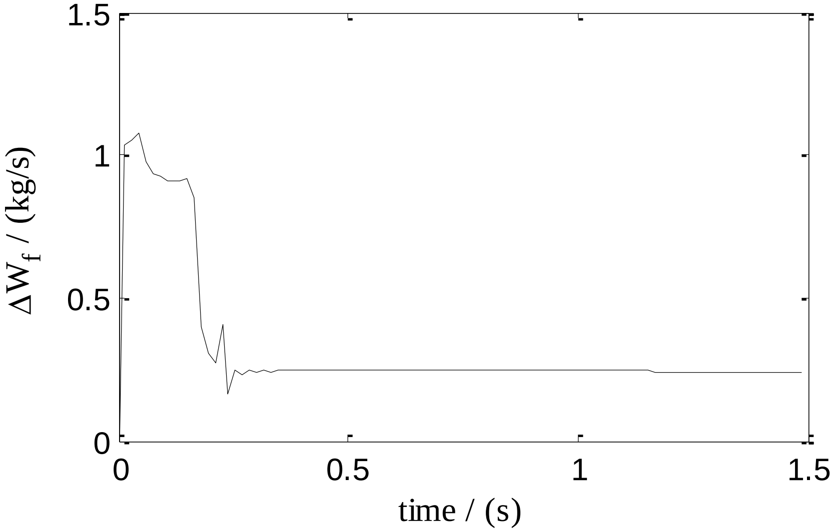


temperature at high-pressure turbine exit

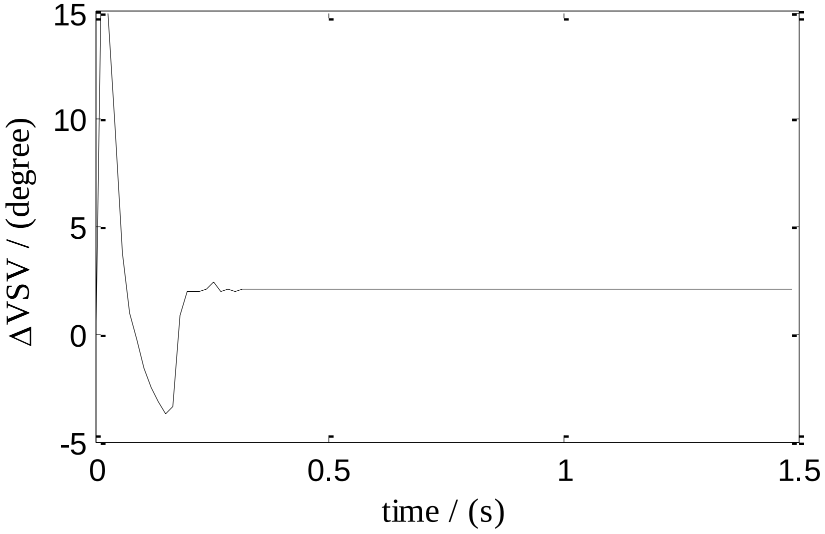


HPC surge margin

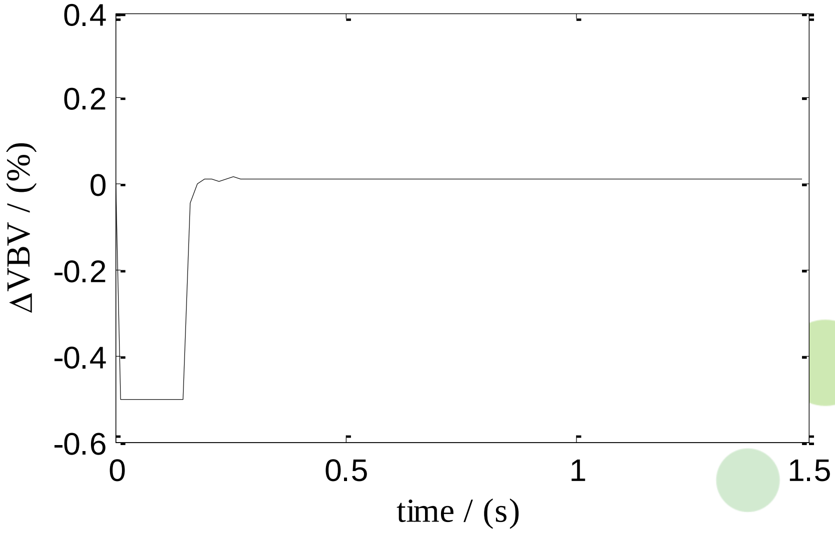
Ⅳ. Simulation and Analysis



Fuel flow



Variable stator vane



Variable bleed valve

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PART FIVE

Conclusion

Ⅴ. Conclusion

- *In order to achieve both decoupling of multivariable control and the optimal performance for aero-engine at the same time, a multivariable dynamic performance seeking control for engine is proposed. the constrained optimization is used to compensate the aero-engine into a decoupled pseudo-linear system. Then classic linear control theory design is applied to design feed-forward and feedback controllers for the pseudo-linear system compensated to complete the closed-loop control synthesis of aero-engine. The testing results show the integrated control system of engine has good decoupling characteristics and dynamic and static response meaning the control architecture designed is feasible and effective.*

Thanks you！

Thanks for Listening