

A DYNAMIC DECOUPLING METHOD FOR CONTROLLING HIGH PERFORMANCE TURBOFAN ENGINES

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Abstract: A new dynamic decoupling method is proposed for controlling complex uncertain systems. Where mathematical modeling is often tedious or inaccurate, the new method uses an unknown input observer (UIO) to estimate and cancel dynamic information in real time. Consequently, controller design and tuning become transparent as the number of required model parameters is reduced. A realistic turbofan simulation, developed by NASA, is used to demonstrate the new design process and compare its performance with that of a supplied benchmark controller. *Copyright 2005 IFAC.*

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1. INTRODUCTION

A great deal of research has been conducted towards the application of modern multivariable control techniques on aircraft engines. The majority of this research has been to control the engine at a single operating point. Among these methods are a multivariable integrator windup protection scheme (Watts and Garg, 1996), a tracking filter and control mode selection for model based control (Adibhatla and Gastineau, 1994), an H_∞ method and linear quadratic Gaussian with loop transfer recovery method (Watts and Garg, 1995), and a performance seeking control method (Adibhatla and Johnson, 1993). Various schemes have been developed to reduce gain scheduling (Garg, 1997) and were even combined with integrator windup protection and H_∞ as well (Frederick *et al.*, 2000).

There have been a limited number of control techniques for full flight operation (Garg, 1997; Polley *et al.*, 1988), but no logical way of tuning the controller for satisfactory performance when applied to an actual engine has yet been discovered. At any given operating point, models become inaccurate from one engine to another. This accuracy increases

with model complexity, and subsequently design and tuning complexity. As a result, very few of these or similar aircraft design studies have led to implementation on an operational vehicle.

The current method for controlling high performance jet engines is still multivariable PI control (Edmunds, 1979; Polley *et al.*, 1988). Although the controller is designed by implementing Bode and Nyquist techniques and is tunable, the problem remains due to the sheer number of tuning parameters compounded by scheduling. Clearly, the objective is to develop a control framework with less tuning parameters than the current approach, while maintaining or even improving performance and robustness.

Recently, disturbance rejection techniques have been used to successfully control complex nonlinear systems. The basic idea is to model a system with an input disturbance that represents any difference between the model and actual system, including external disturbances. By estimating the disturbance in real time, the information is fed back to cancel the disturbance. The system then acts like the model at low frequencies, allowing a controller to be designed around the model. The most common technique is

the disturbance observer (DOB) structure (Endo *et al.*, 1996; Kim *et al.*, 2002; Lee and Tomizuka, 1996; Tesfaye *et al.*, 2000; Umeno and Hori, 1991). Multiple DOBs were used to control a multivariable robot by treating it as a set of decoupled single-input single-output (SISO) systems, each with disturbances that included the coupled dynamics (Bickel and Tomizuka, 1999; Hori *et al.*, 1992; Kwon and Chung, 2002; Schrijver and Dijk, 2002).

Another technique, referred to as the unknown input observer (UIO), estimates the states of both the plant and the disturbance by augmenting a linear plant model with a linear disturbance model (Burl, 1999; Franklin *et al.*, 1998; Johnson, 1971; Liu and Peng, 2002; Profeta *et al.*, 1990; Schrijver and Dijk, 2002). Unlike the DOB structure, the controller and observer can be designed independently. Disturbances (w) are generally modeled using cascaded integrators ($1/s^k$). When they are assumed to be piece-wise constant ($\dot{w}=0$), the observer is simply extended by one state and still demonstrates a high degree of performance.

Originally proposed by Han (1999), active disturbance rejection control (ADRC) is a method that includes all dynamic information in the disturbance, allowing the simplest possible model ($1/s^n$) to be used in designing a UIO, since the actual system converges to this model anyway. The structure was parameterized for transparent tuning by Gao (2003) and a similar two degree-of-freedom (DOF) form was proposed by Miklosovic and Gao (2004). ADRC has already been implemented in many benchmark control problems throughout industry with promising results (Gao *et al.*, 2001a; Goforth, 2004; Hu, 2001; Hou *et al.*, 2001; Huang *et al.*, 2001; Sun and Gao, 2004; Xia *et al.*, 2004). It was also applied to a fairly complex multivariable aircraft control problem (Huang *et al.*, 2001). A generalization of the ADRC framework for n^{th} order multivariable systems is proposed here, as well as its application to turbofan engines.

This paper is organized as follows. Section II proposes a new dynamic decoupling method for uncertain systems. Section III provides an overview of the turbofan model and its supplied benchmark controller. In Section IV, the technique is applied to the jet engine and verified in simulation. The results are then compared with the supplied benchmark controller and discussed in Section V. Finally, Section VI offers concluding remarks.

2. A DYNAMIC DECOUPLING METHOD

Consider a system formed by a set of coupled n^{th} order input-output equations

$$\begin{aligned} y_1^{(n)} &= f_1 + b_1 U \\ &\vdots \\ y_m^{(n)} &= f_m + b_m U \end{aligned} \quad (1)$$

where $y_i^{(n)}$ denotes the n^{th} derivative of y_i . The input $U = [u_1, \dots, u_p]^T$, the output $Y = [y_1, \dots, y_m]^T$, and $b_i = [b_{i,1}, \dots, b_{i,p}]$ for $i=1,2,\dots,m$ and $m \leq p$. Each equation consists of two terms, the instantaneous $b_i U$ and the dynamic $f_i(Y, \dot{Y}, \dots, Y^{(n-1)}, t)$ or simply f_i . All interactions between equations, internal dynamics, and external disturbances are considered part of f_i . The idea is to estimate f_i in real time and cancel it in the control law, reducing the plant to a set of cascaded integrator control problems. The system is rewritten

$$Y^{(n)} = F + B_0 U \quad (2)$$

where $Y^{(n)} = [y_1^{(n)}, \dots, y_m^{(n)}]^T$, $F = [f_1, \dots, f_m]^T$, and $B_0 = [b_1^T, \dots, b_m^T]^T$. Assuming that n is known and that B is an $m \times p$ approximation of B_0 where both are full row rank, a generalized disturbance is defined as $H \equiv F + (B_0 - B)U$. The system reduces to

$$Y^{(n)} = H + BU. \quad (3)$$

Let $X = [X_1^T, X_2^T, \dots, X_{n+1}^T]^T = [Y^T, \dot{Y}^T, \dots, Y^{(n)T}, H^T]^T$ in order to represent the plant with a set of state equations and assign the extended state vector X_{n+1} to the generalized disturbance H .

$$\begin{cases} \dot{X}_1 = X_2 \\ \vdots \\ \dot{X}_{n-1} = X_n \\ \dot{X}_n = X_{n+1} + BU \\ \dot{X}_{n+1} = \dot{H} \end{cases} \quad (4)$$

An extended state observer (ESO) is then designed to track H in real time using Z_{n+1}

$$\begin{cases} \dot{Z}_1 = Z_2 + L_1(E_1) \\ \vdots \\ \dot{Z}_{n-1} = Z_n + L_{n-1}(E_1) \\ \dot{Z}_n = Z_{n+1} + L_n(E_1) + BU \\ \dot{Z}_{n+1} = L_{n+1}(E_1) \end{cases} \quad (5)$$

where $Z = [Z_1^T, Z_2^T, \dots, Z_{n+1}^T]^T$, and the observer error $E_1 = Y - Z_1$. The ESO is written in state space form

$$\begin{aligned} \dot{Z} &= \bar{A}Z + \bar{B}U + \bar{L}(Y - \hat{Y}) \\ \hat{Y} &= \bar{C}Z \end{aligned} \quad (6)$$

$$\bar{A} = \begin{bmatrix} 0_m & I_m & 0_m & \cdots & 0_m \\ 0_m & 0_m & I_m & \cdots & 0_m \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0_m & 0_m & 0_m & \cdots & I_m \\ 0_m & 0_m & 0_m & \cdots & 0_m \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} 0_{m \times p} \\ 0_{m \times p} \\ \vdots \\ B \\ 0_{m \times p} \end{bmatrix}, \quad \bar{L} = \begin{bmatrix} L_1 \\ L_2 \\ \vdots \\ L_n \\ L_{n+1} \end{bmatrix}$$

$$\bar{C} = [I_m \quad 0_m \quad 0_m \quad \cdots \quad 0_m]$$

where \bar{A} is an $m(n+1)$ dimensional square matrix, 0_m and I_m are $m \times m$ zero and identity matrices, and the observer gains L_1, L_2, \dots, L_{n+1} are $m \times m$ matrices, in general. To provide tuning simplicity, the gains are defined to form m parallel observer loops

$$L_j = \text{diag}(l_{j,1}, l_{j,2}, \dots, l_{j,m}), \quad l_{j,i} = \frac{(n+1)!}{j!(n+1-j)!} \omega_{o,i}^j \quad (7)$$

for $j=1,2,\dots,n+1$, by each having $n+1$ observer poles placed in one location at $-\omega_{o,i}$.

$$\lambda_o(s) = |sI - \bar{A} + \bar{L}\bar{C}| = \prod_{i=1}^m (s + \omega_{o,i})^{n+1} \quad (8)$$

When B^+ is the right inverse of B , a disturbance rejection control law is applied to (3), cancelling H .

$$U = B^+(U_0 - Z_{n+1}) \quad (9)$$

This allows a kind of feedback linearization and decoupling to occur which reduces the plant to a set of parallel n -integrator systems at low frequencies.

$$Y^{(n)} = U_0 \quad (10)$$

At this point, any number of control methods may be used. A simple 2-DOF technique, requiring no extra states, is given by Miklosovic and Gao (2004)

$$U_0 = K_0(Y^* - Z_1) - K_1 Z_2 - \dots - K_{n-1} Z_n \quad (11)$$

where Y^* is the desired trajectory for Y and the controller gains K_0, K_1, \dots, K_{n-1} are $m \times m$ matrices in general. Again, the controller gains are defined to form m parallel control loops

$$K_j = \text{diag}(k_{j,1}, k_{j,2}, \dots, k_{j,m}), \quad k_{j,i} = \frac{n!}{j!(n-j)!} \omega_{c,i}^{n-j} \quad (12)$$

for $j=0,1,\dots,n-1$, $\bar{K} = [K_0, K_1, \dots, K_{n-1}]^T$, by each having n controller poles placed in one location, $-\omega_{c,i}$.

$$\lambda_c(s) = |sI - \bar{A} + \bar{K}| = \prod_{i=1}^m (s + \omega_{c,i})^n \quad (13)$$

Remarks:

1. Typically, a nonsingular B^{-1} can be approximated by a diagonal matrix of reciprocal elements, since inaccuracies in B are accounted for in H .
2. The observer is simplified to remove B by substituting (9) into (5).

$$\begin{cases} \dot{Z}_1 = Z_2 + L_1(E_1) \\ \vdots \\ \dot{Z}_{n-1} = Z_n + L_{n-1}(E_1) \\ \dot{Z}_n = L_n(E_1) + U_0 \\ \dot{Z}_{n+1} = L_{n+1}(E_1) \end{cases} \quad (14)$$

3. The commonly used SISO form of ADRC is, in fact, the $m=1$ case.
4. Perhaps robustness and disturbance rejection are both achieved by overcoming f , given that internal uncertainties and external disturbances are both contained within f .
5. A basic tracking controller can be used in place of (11) to improve the tracking error.

$$U_0 = K_0(Y^* - Z_1) + \dots + K_{n-1}(Y^{*(n-1)} - Z_n) + Y^{*(n)} \quad (15)$$

3. TURBOFAN MODEL AND DESIGN SPECIFICATIONS

The Modular Aero-Propulsion System Simulation (MAPSS) package, developed by (Parker and Guo, 2003) at the NASA Glenn Research Center, was used for this demonstration because of its flexibility and availability. A component-level model (CLM) within MAPSS consists of a two-spool, high pressure ratio, low bypass turbofan with mixed-flow afterburning. The engine schematic from Mattingly (1996) is illustrated in Fig 1.

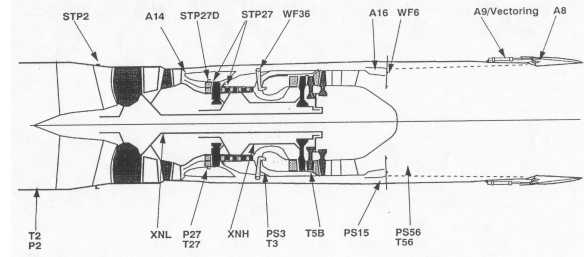


Fig. 1. A Schematic of the Turbofan in MAPSS

The model consists of hundreds of coupled equations and look-up tables that ensure mass, momentum, and energy balances throughout while modeling gas properties effectively. Mathematical details are found in books by Mattingly (1996), Boyce (2002), and Cumpsty (2002). A simplified top-level diagram is illustrated in Fig. 2.

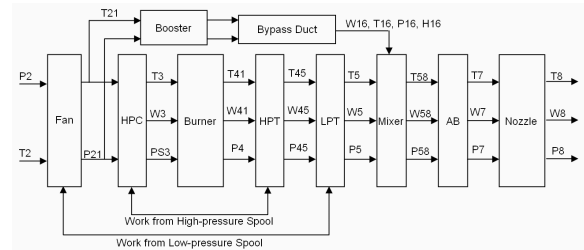


Fig. 2. Engine Components

In general, the CLM is defined by two nonlinear vector equations

$$\begin{aligned} \dot{x}_{CLM} &= f(x_{CLM}, u_{CLM}, p, alt, xm) \\ y_{CLM} &= g(x_{CLM}, u_{CLM}, p, alt, xm) \end{aligned} \quad (16)$$

that are functions of a 3×1 state vector (x_{CLM}), a 7×1 input vector (u_{CLM}), a 10×1 health parameter vector (p), altitude (alt), and Mach number (xm). A 22×1 vector of sensor outputs (y_{CLM}) is combined to

calculate thrust (fn), fan stall ($sm2$) and over-speed ($pcn2r$) margins, engine temperature ratio (etr), and pressure ratios of the engine ($eprs$), liner ($lepr$), and core ($cepr$). These performance parameters form the controlled output.

$$Y = [fn, eprs, lepr, etr, sm2, pcn2r, cepr]^T \quad (17)$$

Each of the seven inputs (u_{CLM}) is controlled by a separate SISO actuator consisting of a torque motor and servomechanism with saturation limits for position, velocity, and current. The first three actuators drive the fuel flow ($wf36$), variable nozzle exit area ($a8$), and rear bypass door variable area ($a16$), respectively. These actuator inputs form the control signal.

$$U = [wf36_{act}, a8_{act}, a16_{act}]^T \quad (18)$$

The remaining four actuators drive stator and guide vane angles using steady state schedules within the primary control loop, ensuring safe operating limits.

The goal of the control system is to achieve a fast thrust response with minimal overshoot and zero steady state error, while maintaining safe rotor speeds, pressure and temperature limits, and stall margins. In MAPSS, the supplied multi-mode controller consists of four multivariable PI regulators, each controlling only three outputs at one time.

$$\begin{aligned} Y_1 &= [fn, eprs, lepr]^T \\ Y_2 &= [fn, etr, lepr]^T \\ Y_3 &= [fn, sm2, lepr]^T \\ Y_4 &= [pcn2r, cepr, lepr]^T \end{aligned} \quad (19)$$

The first regulator controls $eprs$ at low speeds, while the second regulator controls etr at high speeds. The third and fourth regulators actively control limits associated with the fan components, namely the fan stall and over-speed margins when their limits are approached. Limits associated with the engine core are met by acceleration and deceleration schedules on fuel flow (Kreiner and Lietzau, 2003). These schedules along with actuator limits are then placed to constrain the outgoing control signal.

4. TURBOFAN CONTROLLER DESIGN

To demonstrate the process clearly, the new method is applied to the three-input three-output low speed regulator section of the jet engine controller in MAPSS. Since not all of the engine's states are measurable, the model is represented as a nonlinear input-output vector function. Without explicit knowledge of system order, the lowest order case is attempted first

$$\dot{Y} = F(Y, U, p, alt, xm, pla) \quad (20)$$

where the output $Y = Y_1$. When the 3×3 matrix B is used to approximate the high frequency gain of the system, $H(t)$ is defined as

$$H(t) \equiv F(Y, U, p, alt, xm, pla) - BU \quad (21)$$

The system reduces to a form that distinguishes between the instantaneous input and any dynamics to be estimated in real time.

$$\dot{Y} = H(t) + BU \quad (22)$$

The plant is then represented by state equations and X_2 is assigned to track the general disturbance $H(t)$.

$$\begin{cases} \dot{X}_1 = X_2 + BU \\ \dot{X}_2 = \dot{H}(t) \end{cases} \quad (23)$$

The 3×1 state vectors X_1, X_2 are defined as $X = [X_1^T, X_2^T]^T = [Y^T, H(t)^T]^T$. From (14), a simplified ESO is designed such that $Z = [Z_1^T, Z_2^T]^T$ and

$$\begin{cases} \dot{Z}_1 = L_1(Y - Z_1) + U_0 \\ \dot{Z}_2 = L_2(Y - Z_1) \end{cases} \quad (24)$$

$$L_1 = \text{diag}(2\omega_{o,1}, 2\omega_{o,2}, 2\omega_{o,3})$$

$$L_2 = \text{diag}(\omega_{o,1}^2, \omega_{o,2}^2, \omega_{o,3}^2)$$

A disturbance rejection control law

$$U = B^{-1}(U_0 - Z_2) \quad (25)$$

is implemented to decouple the plant, and reduce it to three parallel integrators, $\dot{Y} = U_0$, whereby a simple proportional control law is used.

$$U_0 = \text{diag}(\omega_{c,1}, \omega_{c,2}, \omega_{c,3})(Y^* - Z_1) \quad (26)$$

5. SIMULATION RESULTS

The redesigned low speed regulator, consisting of (24-26), was digitized using Euler integration. The closed loop system was then simulated at ground idle conditions for a step in pla from 21 to 30 with an engine sample time of 0.0004 seconds and a controller sample time of 0.02 seconds. The supplied benchmark controller was put through the same test.

The design process of the benchmark controller involved running the CLM at several operating points to calculate a set of gains from Bode and Nyquist arrays at each operating point. The eighteen gains were each scheduled by six parameters, amounting to a total of 72 possible adjustments that can be made when configuring a single regulator on an actual engine. When running the simulation, these gains changed in percentage (Δ) by the following amounts.

$$\Delta K_p = \begin{bmatrix} 15.2 & 23.2 & -20.0 \\ -186.2 & 205.1 & -9.4 \\ -3.0 & -16.8 & -17.7 \end{bmatrix}, \Delta K_i = \begin{bmatrix} 9.0 & -24.4 & -11.5 \\ 0.2 & 0.1 & 22.4 \\ -5.4 & -8.7 & 3.14 \end{bmatrix}$$

However, the five ADRC gains remained constant throughout the simulation.

$$\omega_{c,i} = 8, \quad \omega_{o,i} = 16, \quad B^{-1} = \text{diag}(.2, -.5, -.5)$$

Each gain, having a clear physical meaning, was quickly tuned on the CLM just as if it would be on an actual engine. The results of both tests are shown in Fig. 3 and Fig. 4.

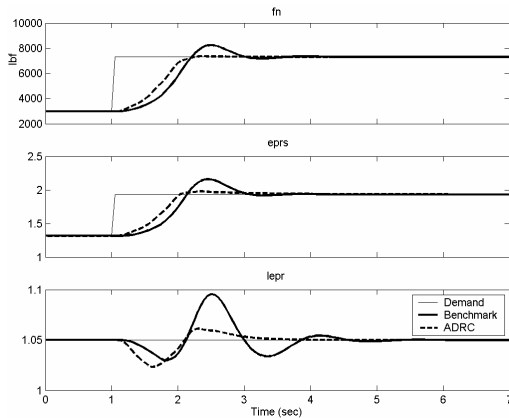


Fig. 3. Comparing Controlled Variables

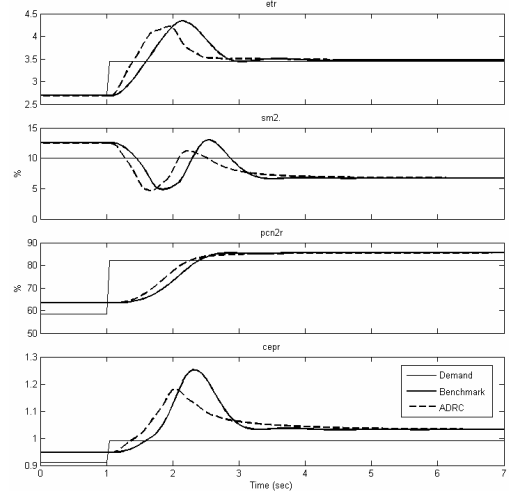


Fig.4. Comparing Uncontrolled Variables

The ADRC controller responded faster to the change in demand levels and with less overshoot than the supplied benchmark controller. Furthermore, the simplest possible control law was used in the ADRC test. The use of more advanced control laws, such as a tracking controller, non-smooth functions described by Han (1999) Gao *et al.* (2001b) and Huang *et al.* (2001) or recent discrete time-optimal techniques are promising options for further improvements in performance. Another possibility is to assume the system is of higher order. Where modern multivariable control schemes are limited, this approach appears well suited for complex nonlinear systems with incomplete model information. The ultimate goal is to offer a degree of tunability to account for variations between engines without

sacrificing performance, while being robust enough to withstand slow degradations from aging or damage.

6. CONCLUDING REMARKS

Preliminary results of these simulation tests on a rather complex turbofan model show the power of the dynamic decoupling method proposed here. Mathematical models are often inaccurate when representing nonlinear multivariable systems. Gain scheduling helps in this area, but makes tuning even worse than it was before. The information needed to effectively control a physical system can be extracted from input-output data in real time and used in the control law without an explicit mathematical model. With this method, the information required of a system is its order (how many integrators there are) and its high frequency gain characteristics.

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