# Research on FOPI control of high bypass ratio turbofan engine based on Min-Max architecture

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**Abstract.** For efficient control of a high bypass ratio turbofan engine, it is desirable that the engine operate as close as possible along its engine limits. With the continuous development of the engine, the performance requirements, especially the response speed, are becoming more and more stringent, and the conservatism of the PI control based on the Min-Max architecture is gradually emphasized, which cannot meet the performance requirements of the engine system. Fractional order control theory is introduced to improve the PI control. Fractional order control theory introduces fractional order integral order for fractional order PI control, which provides a new concept for the performance improvement of the system. Fractional order theory is used to design the FOPI master and limiter and apply to the CMAPSS90K engine model for simulation and analysis, and the simulation results show that the FOPI master and the FOPI control (including the fractional order limiter) can significantly improve the response speed of the system and enhance the performance of the system. The proposed FOPI master of a turbofan engine with high bypass ratio based on the Min-Max architecture can significantly improve the performance of the system, especially the response speed, and reduce the conservatism of the Min-Max architecture.

**Keywords:** Fractional Order Control; Min-Max; High Bypass Ratio Turbofan Engine.

## 1. Introduction

The complexity of a large-contour-ratio turbofan engine is mainly attributed to its complex aerodynamic thermal processes, and its control system requires the system to meet the engine's thrust response requirements while ensuring that the engine's limiting parameters are not exceeded [1,2]. In pursuit of efficient control, it is desirable for its control system to operate as close to its limits as possible [3]. At present, engine control adopts PI control based on Min-Max architecture to achieve its two main functions of thrust control and limiting protection. The traditional PI control structure is simple and easy to maintain. However, with the continuous development of the engine, for its performance requirements, especially the response speed requirements gradually improved [4,5], the traditional PI control cannot meet its performance requirements, and fractional-order control in the traditional PI control on the basis of the improvement, the introduction of new parameters, for the performance enhancement, especially for the response speed enhancement to provide a new approach.

Fractional Order PID (FOPID) control introduces integral order and differential order parameters based on the traditional PID control architecture [6–8]. The introduction of the two parameters makes the control parameters of the FOPID controller more variable, while the integral and differential orders in the PID controller are no longer limited to integers and become adjustable real numbers. There is also a more detailed description of the constraints, which provides better control accuracy than the traditional integer-order PID control and has greater potential for improving the performance of the control system.

Fractional order control was first introduced by Podlubny in 1999, but without specific engineering applications [9]. Since the fractional order control theory introduces two new parameters for the control system and also presents new challenges for the design of the controller and parameter tuning, Martin et al. used the integrated squared error integral to form the cost function, tuned the parameters by the differential evolution algorithm, and controlled the DC motor position output in simulation and experiment, respectively, to verify the feasibility of the algorithm [10]. However, the method of designing the controller in time domain does not consider the performance in frequency domain, so the performance in robustness has not been taken into account. For the robustness problem of fractional order control, Monje et al. proposed the “Monje-Vinagre method”, which is similar to the traditional PID calibration, and it can be realized with parameter tuning in the phase of satisfying the performance conditions of the system [11,12]. Yumuk et al. combined the time-domain performance and frequency-domain performance, considered the gain crossing frequency, phase margin, overshoot, peak time, rise time, and regulation time of the system to design the fractional-order controller, and designed the FOPID controller with fractional-order filtering by utilizing the time-lagged Bode ideal transfer function [13].

For engine control system, there are very few applications using fractional order theory. Wang et al. designed a fractional order PID-nonlinear model prediction method for nonlinear variable cycle engines under non-rated operating conditions to realize direct thrust control of the engine, improve the quality of control, and ensure the accuracy and safety of thrust control under different operating conditions [14]. However, most of the current large-containment-ratio turbofan engines do not have directly measurable thrust, and often use fan speed instead of thrust for control, and the application of fractional-order theory to engine fan control is rare.

Therefore, to address the poor performance and conservatism of the PI-controlled engine based on the Min-Max architecture, we introduce the fractional order theory and the Min-Max architecture, reveals their intrinsic mechanisms, and analyzes the effect of the introduction of the parameter λ to the system by the fractional order theory. Subsequently, based on the fractional order control theory, the FOPI main controller and limiter are designed by combining the CMAPSS90K model with the performance index of the system, and finally, the designed controller is utilized to simulate and analyze the fan speed control on the engine model, and the results show that the FOPI control based on the Min-Max architecture can significantly improve the response speed of the system, enhance the performance of the system, and thus reduce the conservatism of the system.

## 2. Problem Description

Since the fractional order theory has not been studied for a relatively long time, the definition of fractional order calculus by scholars is not uniform at present, and there are several mainstream definitions of fractional order calculus at present.

Definition 2.1 If a function $f(t)$ is producible on the interval $[a, t]$, then the $q$ order Riemann-Liouville fractional order of the function is defined by

$$ {}_aJ_t^q f(t) = \frac{1}{\Gamma(q)}\int_a^t (t-\tau)^{q-1} f(\tau)d\tau, q \in R^+ \tag{1}$$

Definition 2.2 If a function $f(t)$ is producible on the interval $[a, t]$, then the $p$ order Riemann-Liouville fractional order derivative of the function is defined by

$$ {}_a^RD_t^p f(t) \triangleq D^n({}_aJ_t^{n-p} f(t)) = \frac{1}{\Gamma(n-p)}\frac{d^n}{dt^n}\int_a^t (t-\tau)^{n-p-1} f(\tau)d\tau, p \in R^+ \tag{2}$$

where $n$ is a positive integer satisfying $n-1 \leqslant p<n$.

Definition 2.3 If a function $f(t)$ is $n$th-order derivable and producible on the interval $[a, t]$, then the $p$ order Caputo fractional-order derivative of the function is defined by

$$ {}_a^CD_t^p f(t) \triangleq {}_aJ_t^{n-p}(D^n f(t)) = \frac{1}{\Gamma(n-p)}\int_a^t (t-\tau)^{n-p-1} f^{(n)}(\tau)d\tau, p \in R^+ \tag{3}$$

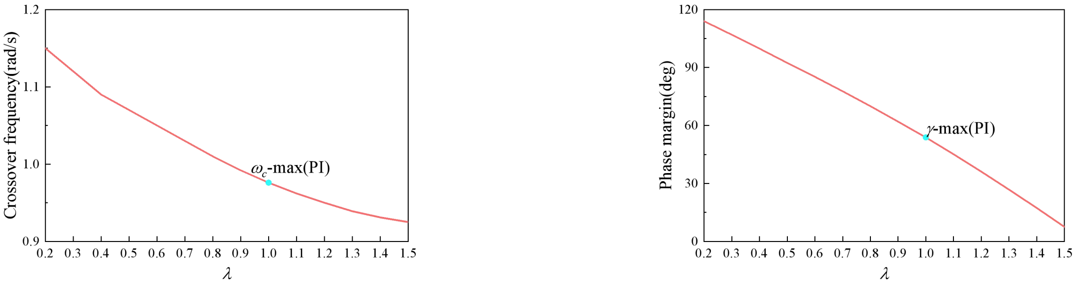
where $n$ is a positive integer satisfying $n-1<p<n$.

Definition 2.4 The p order Crunwald-Letnikov fractional order derivative of a function f(t) is defined by

$$ {}_{a}^{G}D_{t}^{p} f(t) = \lim_{h\to 0} \frac{1}{h^{p}} \sum_{j=0}^{[(t-a)/h]} w_{j}^{(p)} f(t-jh), p \in R^{+} \tag{4} $$

where $w_j^{(p)}$ is a coefficient satisfying $w_j^{(p)}=1$, $w_j^{(p)}=(1-(p+1)/j)w_{j-1}^{(p)}$.

We adopt the Caputo definition, which possesses resolvable lines and accurate physical expressions. To further investigate the effect of the introduction of the integral order $\lambda$ for the system, the FOPI controller is designed and its initial conditions are fixed, and by varying $\lambda$, the open-loop frequency performance metrics of the two are compared traversing the frequency $\omega_c$ and phase margin $\gamma$ in Fig. 1.



(a) Trend of crossing frequency $\omega_c$ as $\lambda$ varies (b) Trend of phase margin $\gamma$ when $\lambda$ varies

Fig. 1 Trend of crossing frequency $\omega_c$ and phase margin $\gamma$ for $\lambda$ variation

From Fig. 1, it can be seen that the conventional PI control due to the limitation of its integration order causes its crossing frequency and phase margin to reach the limiting values under the same conditions. And FOPI as a result of the expansion of its integral order can be the traditional PI control index of the limiting value, and its crossing frequency and phase margin with the decrease of $\lambda$ gradually increase. The introduction of the integral order $\lambda$ provides the possibility of system performance improvement.

## 3. Fractional Order PI Controller Design

A linearized model of a 90,000 lb thrust rating engine at 25,000 ft altitude and Mach 0.62 (FC07) operating conditions obtained from the Commercial Modular Aeronautical Propulsion System (C-MAPSS) is used to design a fractional order PI controller. The engine state space expression is shown in Equation 6, where the engine state and output equilibrium point parameters as well as the limiting values considered are taken from reference[15].

$$ \begin{cases} \dot{x} = Ax + Bu \\ \dot{u} = u_r \\ y_i = C_i x + D_i u \end{cases} \tag{5} $$

$$ u = -Kx $$

Where $x=[\Delta N_f, \Delta N_c]^{\mathrm{T}}$ is the fan speed increment and the core speed increment, which are the state quantities of the system, $u=\Delta W_f$ is the fuel flow increment, which is the system control input, and $y_i$ is the system output increment, where $y_i$, $i=2, 3, 4, 5, 6$ are the system constrained output increments.

The control objective of the system is shown in Equation 6, which requires the system to achieve stable tracking of the fan speed $y_1$ while ensuring that the limiting parameters of the system remain within the limits.

$$\lim_{t\to\infty}|e| = \lim_{t\to\infty}|y_{r1} - y_1| = 0$$

$$\begin{cases} \Delta EPR(y_2 \le \bar{y}_2 = 0.15) \\ \Delta T_{48}(y_3 \le \bar{y}_3 = 400^{\circ}R) \\ \Delta SM_{HPC}(y_4 \ge \underline{y}_4 = -15\%) \\ \Delta Ps3(y_5 \ge \underline{y}_5 = -80psi) \\ \Delta W_f / Ps3(y_6 \ge \underline{y}_6 = -15pph/psi) \end{cases} \tag{6}$$

where e is the value of the deviation between the fan output and the reference input; ΔEPR is the variation of the system pressure ratio, ΔT48 is the variation of the low pressure turbine temperature, ΔSMHPC is the variation of the high-pressure compressor stall margin, ΔPs3 is the variation of the high pressure compressor outlet static pressure, and ΔWf/ΔPs3 is the variation of the fuel/pressure ratio; and $\overline{y}$i is the upper limit value of the system output and $\underline{y}$i is the lower limit value of system output.

The design of proportional-integral control system is generally based on the design of error evaluation index, which is the function integral of the control system instantaneous error *e*(*t*) as an index, including IE, ISE, IAE, ITAE, etc., of which the ITAE index has a better practicability and selectivity, therefore, the design of the main controller of FOPI is carried out using the differential evolution algorithm combined with the ITAE index according to the control requirements, and the parameters of FOPI main controller are optimized by using the differential evolution algorithm to optimize the parameters of FOPI main controller and select the optimal control parameters. The FOPI master controller under Min-Max control architecture is obtained as shown in Equation 7.

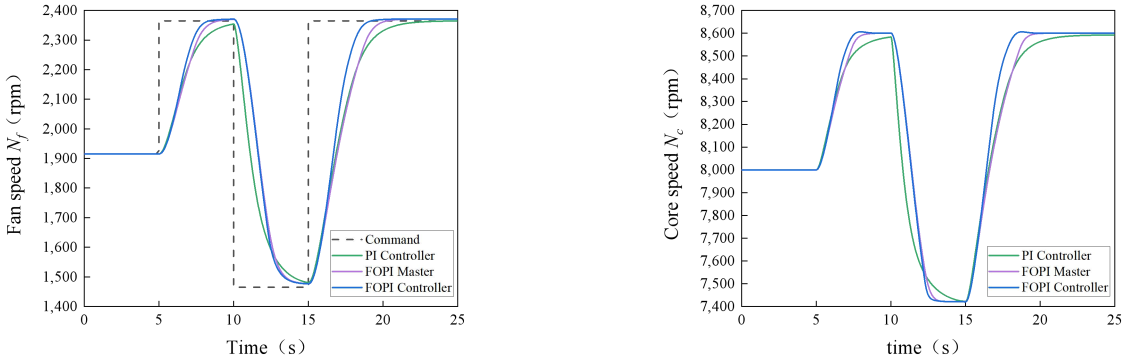
$$K_{N_f}(s) = 0.002 + \frac{0.0004}{s^{0.4}} \tag{7}$$

The differential evolutionary algorithm is further utilized to design the fractional order limiter and the resulting fractional order limiter is shown in equation 8.

$$\begin{aligned} & K_{EPR}(s) = 50 + \frac{0.0002}{s^{0.94}}, K_{T_{48}}(s) = 0.1 + \frac{0.0002}{s^{0.2}}, \\ & K_{SM_{HPC}}(s) = -(0.055 + \frac{0.005}{s^{1.65}}), K_{Ps3}(s) = 0.6 + \frac{0.0001}{s^{0.6}}, \\ & K_{W_f/P_{s3}}(s) = 0.075 + \frac{0.006}{s} \end{aligned} \tag{8}$$

## 4. Simulation

The engine transition state process is designed under FC07 condition, and the fan speed is accelerated from 1915 rpm to 2255 rpm by applying an acceleration command at the 5th second of simulation; the speed is decelerated from 2255 rpm to 1355 rpm by applying a deceleration command at the 10th second; and the speed is accelerated from 1355 rpm to 2255 rpm by applying a large acceleration command at the 15th second. A comparison of the PI, FOPI master and FOPI control fan speed and core speed response based on the Min-Max control architecture is shown in Fig. 2.

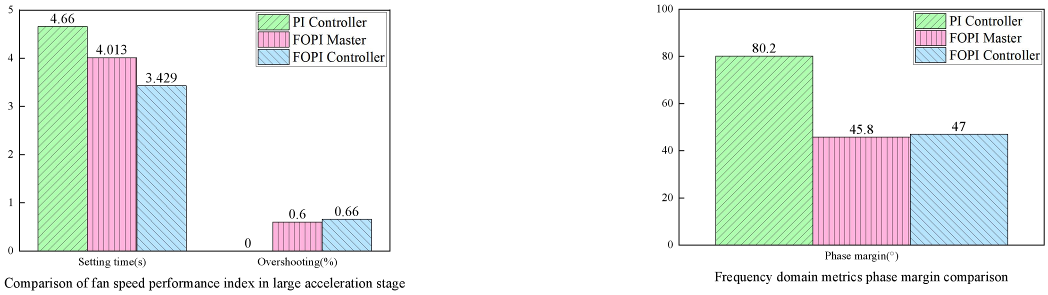


(a) Fan Speed Response Comparison (b) Core Speed Response Comparison

Fig. 2 Comparison of fan speed and core speed response between PI controller and FOPI master under Min-Max architecture

From Fig. 2(a), it can be seen that in the acceleration stage, the fan speed setting time of the PI control under the Min-Max control architecture is 4.17 s, that of the FOPI master control is 3.11 s, and that of the FOPI control is 2.664 s. The response speed of the FOPI control is improved by 25.4% compared to that of the PI control, and that of the FOPI control is improved by 36.12%. In order to compare the performance of the three stages more intuitively, the performance indexes in Fig. 2(a) are analyzed as histograms as shown in Fig. 3.

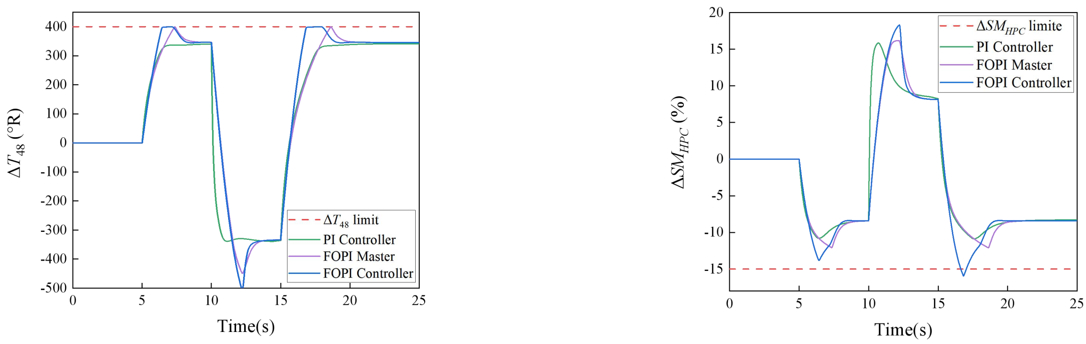
(a) Comparison of fan speed performance index in acceleration stage (b) Comparison of fan speed performance index in deceleration stage



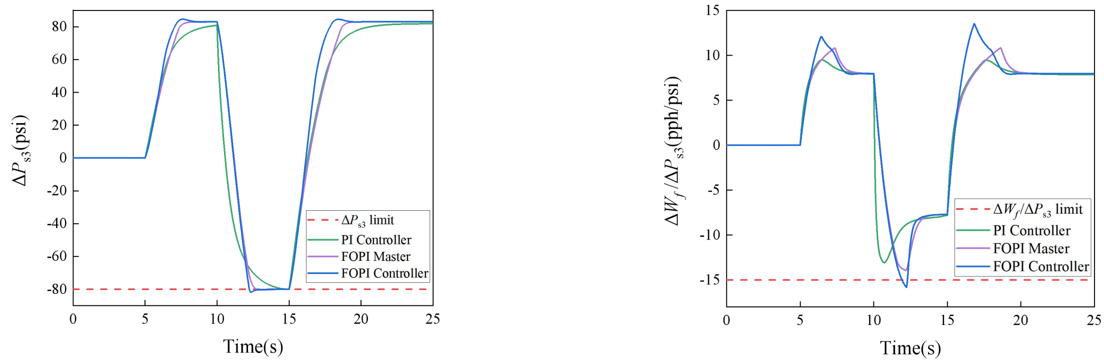
(c) Comparison of fan speed performance index in large acceleration stage (d) Frequency domain metrics phase margin comparison

Fig. 3 Comparison of performance indicators

As shown in Fig. 3, the FOPI master and FOPI controller outperform the PI controller in terms of setting time and overshooting throughout the simulation. The comparison of performance indexes in the acceleration stage is shown in Fig. 3(a), in which the setting time of FOPI control is the shortest and the accuracy of FOPI master is higher; the comparison of performance indexes in the deceleration stage is shown in Fig. 3(b), in which the setting time of FOPI master is the shortest, and the accuracy is similar to that of FOPI control and is the highest; and the comparison of performance indexes in the large acceleration stage is shown in Fig. 3(c), in which the setting time of FOPI controller is the shortest. The comparison of performance indexes in the large acceleration stage is shown in Fig. 3(c), where the FOPI controller has the shortest setting time.



(a) Comparison of $\Delta T_{48}$ (b) Comparison of $\Delta SM_{HPC}$



(c) Comparison of $\Delta P_{s3}$ (d) Comparison of $\Delta W_f/\Delta P_{s3}$

Fig. 4 Comparison of FOPI master and PI controller limit response under Min-Max architecture

To further observe the comparison of the responses of the limiting parameters during the transition, the limiting parameter responses are compared as shown in Fig. 4. As seen in Fig. 4, the response comparison of aero-engine limiting parameters under the control of FOPI master and PI controller under Min-Max architecture shows that both controllers can control the limiting and protection parameters within the limiting values, so that the aero-engine transition state is always in a safe state. From Figs. 4(a)-4(d), it can be seen that the limiting parameters of the PI controller are all at a certain distance from the limiting value, while the FOPI main controller is closer to the limiting value. And the FOPI control in the deceleration phase and large acceleration phase there is a limiting parameter over the limit, which affects the operation safety.

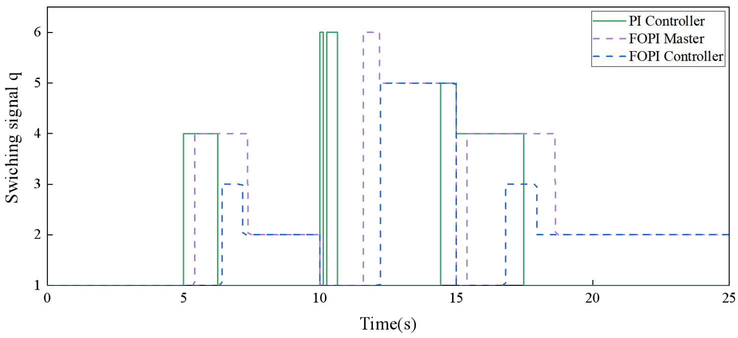


Fig. 5 Comparison of switching signal q between FOPI master and PI controller in Min-Max architecture

As shown in Fig. 5 the state of each controller or limiter, the PI control activates the $\Delta SM_{HPC}$ limiter at the beginning of the acceleration command given, when $\Delta SM_{HPC}$ is far away from its limiting value, in contrast to the FOPI master control which activates the $\Delta SM_{HPC}$ limiter later; in the deceleration phase the PI controller activates the $\Delta W_f/\Delta P_{s3}$ limiter at the beginning of the deceleration command, while the FOPI master controller activates it later. In terms of limiter activation time, the limiter activation time of the PI control is 5.82 s, and the activation time of the FOPI master control is 7.77 s more than that of the PI control, and more limiter activation brings more limiter utilization time.

Simulation results show that the FOPI master control based on Min-Max control architecture can achieve faster fan speed response while ensuring engine safety. The effectiveness as well as the superiority of the Min-Max control architecture's FOPI master is demonstrated by adding more limiter activation time to achieve performance gains during engine transitions. FOPI control based on Min-Max architecture improves the transition state response speed of the system by later limiter activation and shorter limiter activation time, but at the same time, it has obvious deficiencies in limitation management, and parameter overruns occur to different degrees in the deceleration phase as well as in the large acceleration phase due to irrational parameters and mismatches, affecting the safety of the system operation.

## 5. Summary

For the poor performance and conservatism of PI control engine based on Min-Max architecture, we introduce and introduces the fractional order control theory and analyzes that the introduction of integral order $\lambda$ breaks through the performance limitations of traditional PI control. Subsequently, based on the fractional order control theory, combined with the CMAPSS90K model and the performance index of the system, the FOPI master and limiter are designed to control the fan speed simulation, and the results show that the FOPI master and the FOPI control (including the fractional order limiter) can significantly improve the response speed of the system and enhance the performance of the system. The FOPI master is able to better utilize the limiting parameters of the engine to achieve performance improvement through more limiter dwell time, which reduces the conservatism of the Min-Max architecture.

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