American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-4, Issue-12, pp-170-176
www.ajer.org
Research Paper Open Access

An adaptive model predictive controller for turbofan engines

Xian Du*, Yingqing Guo, Hao Sun
Northwestern Polytechnical University, Xi'an 710072, PR China

ABSTRACT: *An adaptive model predictive controller of turbofan engines that can transfer working states within a certain flight envelope was proposed. Due to a very wide range of flight and operation conditions for turbofan engines, a series of model predictive controllers should be well established and arranged. First, constrained linear model predictive control algorithm is investigated and a number of model predictive controllers were designed based on linear models at different nominal points. Then, control domain in the flight envelope was divided according to the inlet parameters of aero-engines, and the nominal points were determined in all subsections. Finally, an adaptive predictive controller was achieved using a multilayer parameters scheduling scheme, which possesses the ability to realize the regulation of engines under different flight and working conditions. Simulation results show that the proposed adaptive predictive control system displays good performances in the control domain, which provides an effective approach for the design of the whole envelope controller.*

Keywords - *Turbofan engine, transition state, adaptive model predictive control, flight envelope, parameters scheduling*

I. INTRODUCTION

In the process of aero-engine control, input and output variables are subject to all kinds of physical and operational limits [1-3]. For example, a fuel flow metering valve, as one of the actuators, cannot deal with too fast of a fuel flow rate fluctuation arbitrarily due to mechanical or hydraulic limit; and the controlled output rotor speeds or exhaust temperature cannot exceed their limits for security reasons. In addition, a variety of sensors are also limited due to their measuring range, therefore, an unconstrained control system cannot exist. Not only limit management, but also good dynamic response is a critical element in the aero-engine control [4]. With the increasing complexity and improved performance of aero-engines, commercial and military aircraft put forward higher requirements on the control of the propulsion system, where advanced control method is the main way to face this challenge [5]. Model predictive control (MPC) is a kind of advanced closed-loop optimization strategy, which has the ability to process all kinds of constraints directly and conveniently [6-7], and be more powerful than traditional PID control method [8].

In general, predictive controller could adapt to a wide range of disturbances and achieve good control performance, even in the case of a model mismatch [9]. For aero-engines, which are nonlinear complex systems, it is difficult to ensure that a predictive controller can achieve satisfactory dynamic response in the full flight envelope. Specifically, taking a predictive controller based on a fixed linear engine model as an example, a series of simulations are conducted in the entire flight envelope at step inputs. The results showed that the system is stable with no steady-state error in any sections and is able to meet the control requirements. While in some parts, there exist large overshoot, frequent oscillations, and even instability during the transitions, which is beyond the scope of performance requirements [10].

In this paper, a multilayer parameter scheduling scheme is proposed to design an adaptive model predictive controller for a commercial turbofan engine. The rest of the paper is organized as follows. Section II introduces the mathematical models of the turbofan engine and the design of model predictive controllers at nominal points. The regional divisions about the control domain in the envelope are established in Section III. Section IV investigates the multilayer parameters scheduling scheme to construct an adaptive model predictive controller. Section V discusses the model predictive controller design for acceleration/deceleration transition state and analyzes the simulation results. The conclusions are summarized in Section VI.

II. MODEL PREDICTIVE CONTROLLER DESIGN AT NOMINAL POINTS

For a certain type of high bypass commercial turbofan engine, the literature [11] realizes the usage of a packaged component level nonlinear dynamic model in Matlab/Simulink platform via dynamic link library technology, which was originally constructed and tested perfectly in the GasTurb software. To design model predictive controllers at nominal points, linear engine models are obtained using the fitting method at given flight conditions and working states. Note that the final adaptive model predictive controller based on multilayer parameters scheduling scheme is tested in the nonlinear component level engine model, although a series of linearized models are prepared for model predictive control designs.

The purpose of an aero-engines control system is to provide required thrust by changing fuel flow according to throttle positions [1]. However, in practice, thrust cannot be sensed and therefore cannot be controlled directly. Generally, speeds or engine pressure (EPR) is used as the indicator of thrust. In this paper, the control objective is to track fan speed setpoints while considering input and output constraints. Therefore, discrete single-input state space based linear models of the engine can be expressed as:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) + Du(k) \end{cases} \tag{1}$$

where $x = \left[\Delta N_f \quad \Delta N_c\right]^T$, $u = \Delta W_f$, $y = [\Delta N_f \quad \Delta T_{45} \quad \Delta smHPC]^T$ .The control variable is the deviations of fuel flow (W_f) in kg/s from the steady state, state variables are the deviations of fan speed N_f and core speed N_c in r/min. Three output variables are considered here, where fan speed is used for tracking and the other two output variables (high pressure compressor outlet temperature ΔT_{45} in $^\circ R$ and high pressure compressor stall margin $\Delta smHPC$ in %) are regarded as limited outputs. The values of matrices A, B, C and D are different corresponding to different flight conditions (e.g. flight altitude *H* and Mach number *Ma*) and working states (expressed as a percentage of the max cruise speed or fan speed N_f).

Model predictive control algorithm consists of three parts [9]: predictive model, receding horizon optimization and feedback emendation. Eq.(1) is utilized as the predictive model. The cost function of the optimization section is defined as follows:

$$\begin{aligned} & J = \sum_{i=1}^{i=n_y} e(k+i)^T e(k+i) + \lambda \sum_{i=0}^{n_u-1} \Delta u(k+i)^T \Delta u(k+i) \\ & s.t. \quad U\min \le u(k+i) \le U\max \qquad i = 0,1..n_u - 1 \\ & \qquad Y\min \le y(k+i) \le Y\max \qquad i = 1,\ldots n_y \end{aligned} \tag{2}$$

where $e(k+i) = r(k+i) - y(k+i)$. $r(k+i)$ is the reference value. $y(k+i)$ and $\Delta u(k+i)$ are the predicted outputs and inputs in the future *i* time steps respectively. $U\max$, $U\min$ represent the maximum and minimum input constraints. $Y\min$, $Y\max$ indicate the output constraints. n_u and n_y are control horizon and prediction horizon respectively. $\lambda > 0$, is the control variable weight. As for feedback emendation, a simple method that correct the reference values according to the errors between the actual N_f output and the predicted N_f output at every sampling time is used, which can be defined as:

$$\delta(k+1) = q \times (N_f - \hat{N}_f) \tag{3}$$

where q is the correction factor, which can be adjusted by trial-and-try.

Conveniently, graphical user interface (GUI) design toolbox in MATLAB/Simulink can be used to design model predictive controllers at nominal points. Key parameters mentioned above are included in the Graphical design interface. According to the influences of each parameter on the system, appropriate values can be finally tuned based on simulation results at nominal points for these model predictive controllers.

III. DIVISIONS OF THE CONTROL DOMAIN AND THE SELECTION OF NOMINAL POINTS

It is supposed that the control domain, part of the entire flight envelope, considered in this paper is shown in Fig.1.

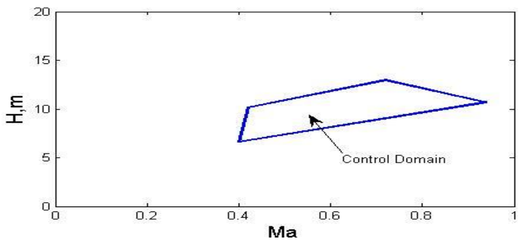

Fig.1 Control domain

Although MPC has good robustness, simulation results show that one predictive controller alone cannot satisfy the requirements of dynamic performance for the turbofan engine in the entire control domain, as shown in Fig.2, where the nominal point is *H*=11km, *Ma*=0.8, and power=100%.

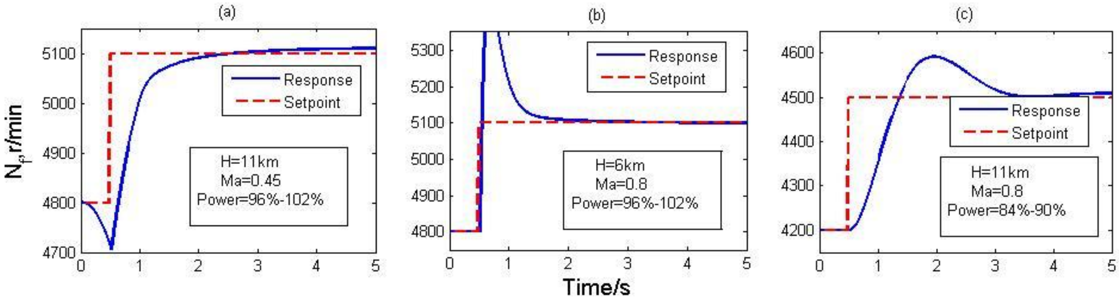

Fig. 2 N_f response at non-nominal points

Fig. 2(a) shows that the response speed is too slow when *Ma* is far from its nominal point; Fig. 2(b) represents that the overshoot is too large when *H* is off its nominal point; and bad dynamic response appears when working state is off its nominal point, as shown in Fig. 2(c). After all, model predictive controllers are designed based on small deviation linear dynamic models, which are only applicable to small areas around nominal points for better dynamic response. In order to obtain better control effects, the control domain should be divided into subsections and a reasonable nominal point is to be picked out for each subsection. In this way, a series of model predictive controllers can be designed for subsections, ensuring the performance requirements in the whole control domain.

In this paper, the control domain is divided according to the relative variation of aero-engine inlet parameters [12]. For the given fuel flow supply and the fixed nozzle area, the fan speed and the turbine expansion ratio, as well as other engine outputs are a function of only the flight altitude *H* and Mach number *Ma*. Furthermore, if the inlet of the turbofan engine is determined, the total temperature *T*1 and total pressure *P*1 of inlet are a function of *H* and *Ma*, as presented in Eqs.(4) and (5). Therefore, it can be concluded that the small deviation linear state space models are closely related to parameters *P*1 and *T*1.

When H≤11km, there exists:

$$\begin{cases} T1 = (288.15 - 6.5 \times H) \times (1 + 0.2 \times Ma^2) - 273 \\ P1 = 1.03323 \times (1 - \dfrac{H}{44.3})^{5.2553} \times (1 + 0.2 \times Ma^2)^{3.5} \end{cases} \tag{4}$$

When H>11km, there exists

$$\begin{cases} T1 = 216.6 \times (1 + 0.2 \times Ma^2) - 273 \\ P1 = 0.2314 \times e^{(\frac{11-H}{6.318})} \times (1 + 0.2 \times Ma^2)^{3.5} \end{cases} \tag{5}$$

If the sensed parameters *T*1 and *P*1 change within a certain small range, it is assumed that a model predictive controller can be used to regulate this subsection. So the selection rules J for subsection divisions can be defined as:

$$J = \sqrt{(\frac{P1_x - P1_0}{P1_0})^2 + (\frac{T1_x - T1_0}{T1_0})^2} \le \varepsilon \tag{6}$$

where $P1_0, T1_0$ are the inlet total pressure and temperature at nominal points respectively, $P1_x, T1_x$ are the inlet total pressure and temperature at a given place in this control domain, and ε is the acceptable range from nominal points.

Simulation results show that when $\varepsilon \le 0.2$, good dynamic and static performance can be achieved within the subsection by one controller that was designed based on nominal points. Here, ε is selected as $\varepsilon = 0.2$ and nominal points should be chosen so that their subsections can cover the entire control domain. Through continuous attempts, three nominal points in the control domain are finally selected as (H=11km, Ma=0.8), (H=11.7km, Ma=0.65) and (H=9.5km, Ma=0.75), as pointed out by "*" in Fig.3. Different colors in Fig.3 represent different subsections. It can be seen that the predictive controller designed at these three nominal points can cover the entire control domain.

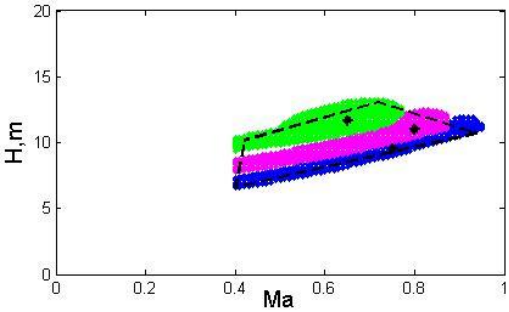

Fig. 3 Nominal points and subsections

In addition, if the control domain is extended to the whole flight envelope, the method for regional divisions and nominal point selections is the same, but a few more nominal points must be chosen to cover the full envelope, which increases the workload. In this paper, we just take a part of the whole envelope, known as control domain, for example.

IV. MULTILAYER PARAMETERS SCHEDULING SCHEME

In this paper, an adaptive predictive controller is designed to realize the control of the turbofan engine that work from 80% to105% speed changes in the entire control domain (*H*, *Ma*) of Fig.1.

Take three speed nominal points 85%, 93% and 100% for example, covering the 80%-105% working states. Considering the fact that there are three flight nominal points in the control domain in Fig.3, a total of $3 \times 3 = 9$ nominal points need to be included under different working states and flight conditions, as listed in Table 1.

Table.1 Different Nominal Points (NP)

NP	Power	Speed (r/min)	*H* (km)	*Ma*
1	85%	4250	9.5	0.75
2	85%	4250	11	0.8
3	85%	4250	11.7	0.65
4	93%	4650	9.5	0.75
5	93%	4650	11	0.8
6	93%	4650	11.7	0.65
7	100%	5000	9.5	0.75
8	100%	5000	11	0.8
9	100%	5000	11.7	0.65

A multilayer parameters scheduling scheme is proposed to design the adaptive predictive controller, as shown in Fig. 4.

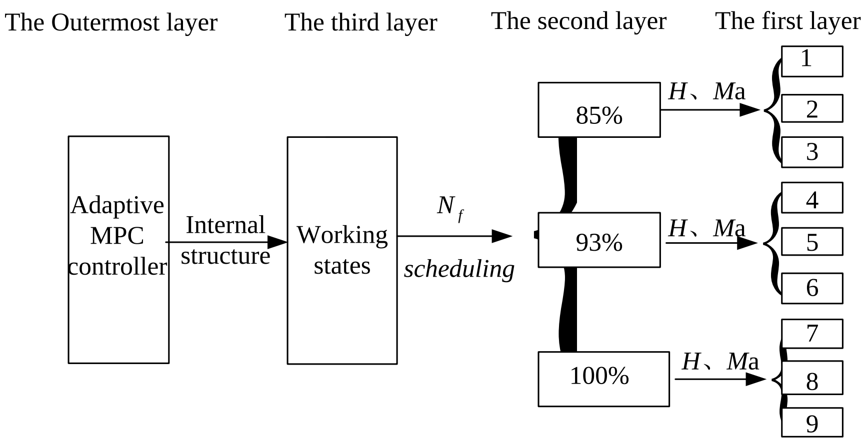

Fig. 4 The principle diagram of the multilayer structure

In the first layer, the 9 predictive controllers are designed based on 9 different working states and flight conditions, where numbers 1 to 9 correspond to the 9 different nominal points in Table 1. As mentioned in Section II, each MPC controller in this layer can only control the working states and flight conditions around the nominal speeds and nominal flight points.

There are three MPC controllers in the second layer, each of which can achieve the management of the entire control domain around a certain nominal speed state. Every MPC controller in the second layer dispatches the three corresponding controllers in the first layer according to the flight altitude H and Mach number Ma, which has been discussed in Section III.

The MPC controller in the third layer owns the ability to realize the objective that the turbofan engine can operate randomly during 80%-105% working states in the entire control domain. The fan speed N_f is used as the scheduling variable to regulate the MPC controllers in the second layer (detailed descriptions will be followed later). Therefore, the MPC controller in the third layer can govern all the 9 controllers in the first layer. In this multilayer format, the design of an adaptive model predictive controller is accomplished, being able to realize the scheduling process based on the working states being expressed as N_f , and the flight conditions expressed as H and Ma at that point in time.

The outermost layer is the external structure of the third layer, which has the purpose of making the adaptive predictive controller intuitive and clear. The inputs of the outermost layer is composed of fan speed N_f , the driver's instruction (the percentage of the speed), the flight attitude H, as well as the Mach number Ma, and the output is the main fuel flow W_f.

Now we turn our attention to the principle of the third layer as it relates to how the fan speed N_f is utilized as the scheduling parameter variable. A set of linear MPC controllers are obtained based on different speed nominal points, and the switching problem between two adjacent MPC controllers at speed nominal points need to be studied to ensure the smooth transitions. From Table 1, it is obvious that working states (expressed as a percentage of the max cruise speed) correspond to a fixed physical speed at steady state. Therefore, the fan speed N_f can be chosen as the scheduling variable. For any working state between k and k+1, two nominal points, the output value of the adaptive predictive controller (fuel flow) is obtained by interpolation of the output values of the MPC controllers based on the k and k+1 nominal points. In other words, N_f is used to describe the current fan speed, whereas N_{fk} and $N_{f(k+1)}$ indicate the steady-state speed corresponding to the k and k+1 nominal points. Control variables W_{fk} and $W_{f(k+1)}$ are the control values corresponding to the k and k+1 nominal points. Suppose that the inequalities $N_{fk} \le N_f \le N_{f(k+1)}$ hold, then the final output value u_{cmd} of the adaptive predictive controller can be defined as:

$$u_{cmd} = W_{fk} + \frac{N_f - N_{fk}}{N_{f(k+1)} - N_{fk}} \times (W_{f(k+1)} - W_{fk}) \qquad (7)$$

Next, simulations are studied to verify the effectiveness of the proposed adaptive model predictive controller. The controller is connected with the packaged nonlinear component level engine model in the Matlab/Simulink platform.

The control objective here is to maintain the working states, regardless of the changes in the flight conditions. In this example, the desired working state is 90% (N_f equals 4500r/min), and the flight conditions (H, Ma) changes frequently with time, as shown in Fig. 5. In this situation, the changes of flight conditions can also be regarded as disturbances applied to the system. The input and output dynamic responses are then displayed in Fig.5.

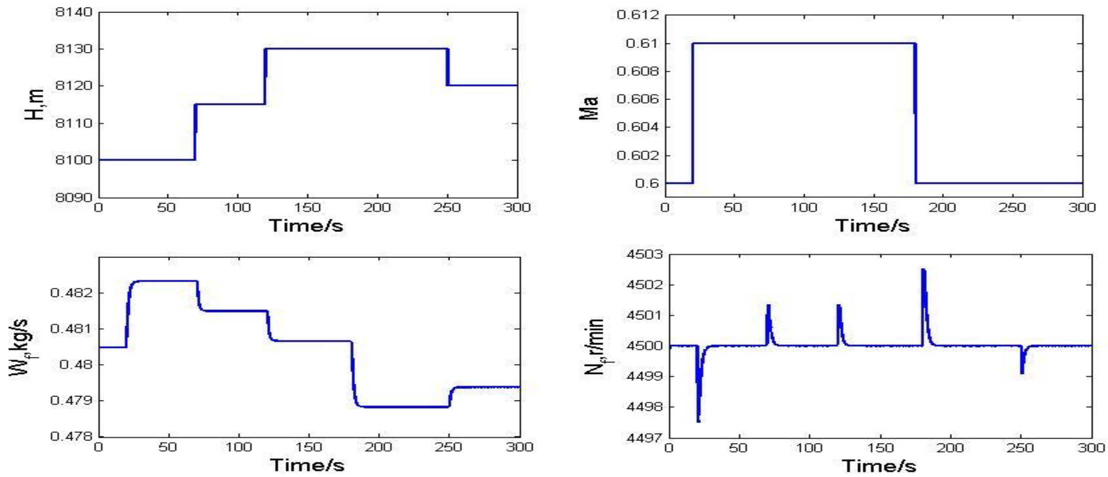

Fig. 5 Input and output response with flight conditions changes

In Fig.5, it is observed that when flight conditions change, the regulated output N_f can be restored to the original setpoint in a very short time with minor deviations, which indicates that the MPC controller can deal with flight disturbances in an effective manner during the steady state. Similarly, for other desired N_f constant values, it can be validated that the control effects under small disturbances are consistent with good disturbance rejection.

V. DESIGN FOR ACCELERATION AND DECELERATION TRANSITION STATE

The controller design of transition state accounts for a large part of aero-engine control system. During the transition state, a variety of limits should be considered to ensure the safe operation of aero-engines, such as speeds limits, temperature limits, compressor stall margin limits and both acceleration and deceleration limits. In this paper, only the acceleration and deceleration design for transition state is considered, which is based on schedule scheme [1].

This method involves the acceleration and deceleration schedule. In other words, the idea of an acceleration schedule is to limit the maximum change rate of fuel flow WFM. On the contrary, the deceleration schedule control is to limit the minimum change rate of fuel flow WFM. Unlike traditional transition controls (e.g. PID controller) where anti-windup (IWU) must be taken into account, MPC is well-known as a good way to deal with input constraints directly within the process of optimizations. However, such constraints are not included in the conventional control algorithms, which cannot produce a control input that breaks away from constraints to overcome the "IWU" phenomenon. Therefore, for the adaptive MPC controller, there is no need to consider the "IWU" problem during the transition state.

Suppose the maximum limit of the W_f change rate is 0.35kg/s for the acceleration schedule and the minimum limit is -0.25kg/s for deceleration schedule based on the equilibrium values at steady state. In addition, output limits, $\Delta T_{45} \le 600K$ and $\Delta smHPC \ge -20\%$ are also taken into account during the transition state. These constraints are then added to the adaptive MPC controller designed in Section IV. The acceleration and deceleration simulations of transition state are then carried out to realize the working states transfers for a large range from 80% to 105% (N_f, 4200r/min-5200r/min), as shown in Fig.6.

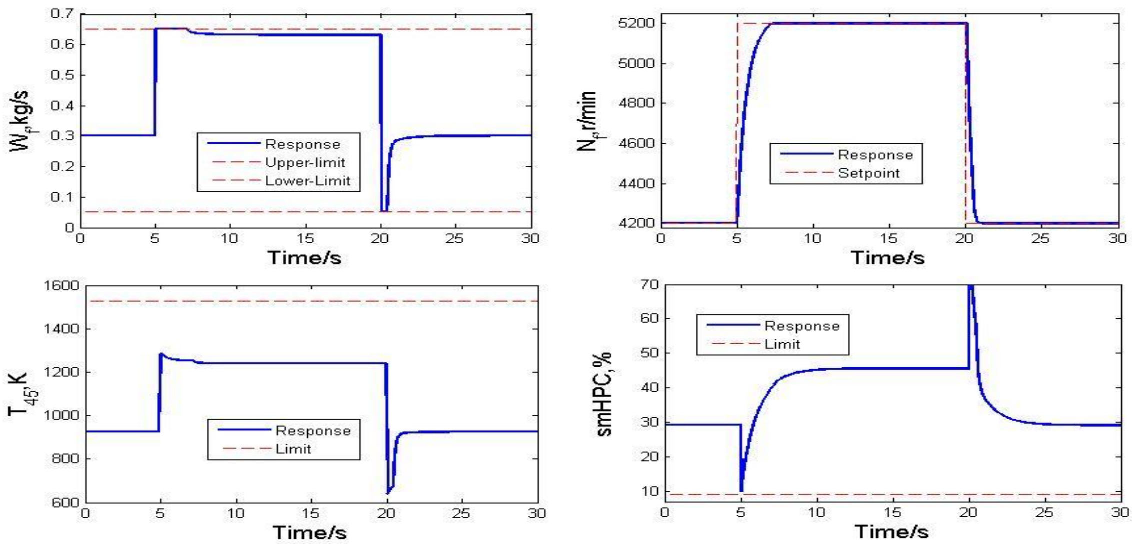

Fig. 6 Response during transition state

As seen in Fig.6, acceleration and deceleration schedules play an important role in the process of transition state changes, where the maximum increments are limited to 0.35kg/s and the minimum increments are limited to -0.25kg/s compared with equilibrium values at steady state. It is shown that N_f can track the setpoints with good dynamic performance. In addition, the steady-state adaptive MPC controller operates in the first 0s-5s, then the acceleration schedule works during 5s-7s, followed by the steady-state controller working during 7s-20s, and then the deceleration schedule takes over to work in 20s-21s, with the steady-state controller working again at the end. It is also observed that the change values of limited outputs, ΔT_{45} and $\Delta smHPC$, are within their limits during the transition state.

The simulation results show that the designed adaptive MPC controller meets the performance requirements of both the steady state and the transition state processes. Therefore, it is feasible for the adaptive MPC controller to be applied into turbofan engines.

VI. Conclusions

An adaptive model predictive controller based on multilayer scheduling scheme was designed and tested with nonlinear component level turbofan engine model, which can drive the engine to operate randomly under the working states from 80% to 105% in the entire control domain. Acceleration and deceleration schedules are realized by adding input constraints to the control system. In addition, the output constraints can also be considered in the adaptive MPC controller. Although the control domain considered in this paper is just a section of the full flight envelope, the method to divide the entire envelope is the same, and so it is easy to extend the controller to realize the control in the whole flight envelope. For the similar reason, wider working states can also be achieved using the multilayer parameters scheduling scheme. Therefore, the method proposed in this paper gives instructions for the controller design involving the whole working states and the entire flight envelope.

References

[1] L. C.Jaw, J. D.Mattingly, Aircraft Engine Controls Design, System Analysis and Health Monitoring. *Reston: AIAA,* 2009: 96 – 100.

[2] J. Csank, R. D. May, J. S. Litt, and T. H. Guo: *Control design for a generic commercial aircraft engine, AIAA* 2010-6629.

[3] H. Richter: *Advanced control of turbofan engines*. Springer New York, 2012, pp. 203-250.

[4] Thompson, J. Hacker, C. Cao. *Adaptive engine control in the presence of output limits, AIAA* 2010-3492.

[5] G. Nathan. *Intelligent engine systems—Adaptive Control. NASA/*CR-2008-215240

[6] H.X. Qiao, S. Q. Fan, L. Yang. Constrained predictive control based on state space model of aero-engine. *Journal of Propulsion technology, 26(6) , 2005,* 548-551.

[7] X. Du, Y.Q. Guo, X.L. Chen. Multivariable constrained predictive control and its application to a commercial turbofan engine. *Advanced Materials Research,* V*ol.909,* 2014, 281-287.

[8] X. Du, Y.Q. Guo, X.L. Chen. MPC based active fault tolerant control of a commercial turbofan engine. *Journal of Propulsion Technology, 36(8)*, 2015, 1242-1247

[9] J. X. Qian, J. Zhao, Z. H. *Xu. Predictive Control.* Beijing: Chemical Industry Press, 2007.

[10] H. X. Qiao, S. Q. Fan. Predictive control of aero-engine with model mismatching. *Journal of Propulsion technology,* 27 (5), 2006, 455-458.

[11] S. G. Zhang, Y.Q. Guo, J. Lu. Component level model of Aero-engine based on GasTurb / MATLAB and its Implementation. *Journal of Aerospace Power, 35(2),* 2014, 381-390.

[12] H.Q Wang, Y.Q. Guo. Design of Full Flight Envelop Controller for Aero-Engine. *Measurement and control technology,* 28(5), 2009, 48-51.