UKACC International Conference on Control 2012
Cardiff, UK, 3-5 September 2012

Command Switching Strategy Based Safety Protection Control for Aeroengines

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Abstract—**Based on the simplified hypersonic air-breathing propulsion model, this paper studies the output regulation/ safety protection multi-objective switching control problem focusing on the safety boundaries existing during the working progressing. Command switching strategy based on the safety margin is researched. In the safe region with a sufficiently large safety margin, the regulation loop is active and the regulated output is controlled to track the reference signal as quickly as possible. But the protected loop will be switched on and the protected output will be forced to escape from dangers once the safety boundaries approach. A dynamical state feedback controller and a protection controller work in turn in a hysteresis switching way to guarantee the asymptotic tracking with certain safety performance. The conditions under which the asymptotic tracking could be guaranteed are given and the control parameters could be calculated by solving optimal problems. It is pointed out in this paper that the designing of the regulation controller and the protection controller could be implemented separately, and the control parameters could be optimized to get certain optimal performance index using numerical method. Finally, simulation researches are performed to verify the effectiveness of the given methods, which also indicate that the commands switching control can improve both safety margin and the dynamical performance indices than the single controller.**

Keywords-command switching control; safety protection; aeroengine; safety margin; optimization; tracking

I. INTRODUCTION

There have been dramatically large amounts of attentions attracted by the modeling and control of hypersonic air-breathing propulsion in the recent years [1], especially since the successful flight experiment of the X-51 aircraft in late May 2010. Usually, a hypersonic air-breathing vehicle is driven by a scramjet engine, and is with the integrated airframe/ scramjet configuration which causes strong couplings among flight dynamics, aerodynamics, propulsion and control [2]. The coupled dynamics results in various engine safety boundaries during the working progressing of a hypersonic air-breathing vehicle, for example, the combustion stabilization boundary, the combustor wall temperature limitation, the inlet channel unstarting boundary, and so on. Disastrous accidents may happen once the system works outside the safety boundaries or even approaches them. On the other hand, due to the requirement of air and space travel, hypersonic vehicle must have a broader flight envelope than any other aircrafts, which brings large parametric uncertainties and quick dynamical changes. To pursue more excellent flight performances, the hypersonic air-breathing vehicles are usually required to flight near the safety boundaries as possible as it can. In order to balance the contradiction between the performance and safety, protection measures must be taken to the hypersonic air-breathing vehicle when it is approaching the safety boundaries. And one of the effective measures to finish this objective is to adopt the multi-objective switching control strategy [3].

When asked to tracking a large step command as quickly as possible, it is necessary to design regulating/protecting switching controllers for a hypersonic air-breathing vehicle since, in common sense, it is obviously that the rapidity usually conflicts with the security. A regulation/protection switching control system consists of a regulation loop and several protection loops, when the controlled plant is working within the allowed safety limits, the regulation loop works to achieve perfect performances, when the controlled plant trends towards the neighborhood of some safety boundary, the corresponding protection loop will be switched on automatically according to certain previous design to ensure safety. The protection loops are expected to be constructed according to the boundaries so that the designers could relax the safety condition when they are dealing with the regulation loop. It is with more efficiency and is less conservative.

It is notable that the safety protection control problem is similar to the state constrained control problem which is studied via the barrier Lyapunov function in [4], but there are differences between them. First, for example, not only boundary but also transient performances, especially that of the states except the constrained ones, should be considered in the safety protection control problem. Second, the safety protection controller is usually expected to be designed separately from the regulation controller, and sufficient safety margin is also usually needed.

Consisting of the determination of both the controllers and the switching law, design of the switching controller is a complex synthesis procedure of nonlinear controller, even it is for a linear plant. A systematic designing method for the safety protection switching controller is anticipated to come out, by

This work was supported in part by the NSFC under Grants 61174073, 90816028, 61174058 and 61004020, and the FRFCU under Grant N100604005, and the Program for New Century Excellent Talents in University NCET-09-0257, and the Fundamental Research Funds for the Central Universities DUT11SX07.

both the researchers working on the switched systems theory and the engineers working on the practical fields. Most of the currently existing theory results [5], however, focus only on the analysis of stability of switched systems, and few of the switching laws present in the existing theoretical results are so easy to implement. And few results can be referred to design regulation/protection switching controllers. The work [6] uses switching static feedback controller with the maximum control switching law to deal with the constant tracking problem for a linear system with state constraints, but the dynamical response performance is not discussed. In [3], the regulation/ protection switching controller based on the minimum law is studied through simulation, without stability analysis and designing steps mentioned. In our previous work [7] and [8], the switching control based on minimum control switching law and the command switching control scheme are investigated respectively.

Based on our previous work in [8], this paper continue to studies the output regulation/safety protection control problem for the simplified model of the aeroengine via command switching control based on the safety margin. Several modifications are performed to improve the response performance. The proposed asymptotic tracking condition could be used to design the control parameters through solving programming problems. The design of the regulation loop and the protection loop can be finished in steps, and the control parameters can be optimized in a numerical method to get optimal ITEA index. Conditions for the finite times switching and estimation of the safety margin are also mentioned. Finally, in the section of simulation researches, the effectiveness of the given results verified, and it is revealed that the proposed command switching strategy is with superiority both in safety performance and ITAE (Integral of Time-weighted Absolute Error) index comparing to the single controller scheme.

II. PROBLEM DEPICTION

As is shown in Figure 1, the linear system studied in this paper can be considered as the simplified model of a hypersonic air-breathing propulsion, where the actuator and the basic engine are simply modeled as inertia units $G_1(s)$ and $G_2(s)$ respectively, while the temperature sensor is considered as a leading unit $G_3(s)$ approximately, where

$$G_1(s)=\frac{1}{T_4 s+1},\quad G_2(s)=\frac{1}{T_3 s+1},\quad G_3(s)=\frac{T_1 s+1}{T_2 s+1}.$$

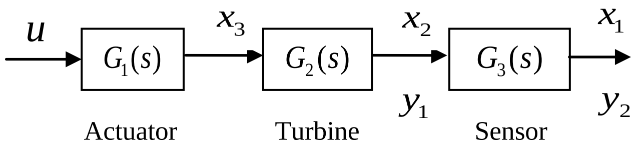

Figure 1. A simplified model of hypersonic air-breathing propulsion

As the regulated output, the rotation velocity of the turbine is expected to track the reference signal as quick as possible. Simultaneously, however, as the protected output, the temperature is not allowed to touch the constant safety boundary. To make the state available, the state variables x_1, x_2 and x_3 are chosen as the temperature, the rotation speed and the output of the actuator respectively, the state space model of the plant is

$$\dot{x}=Ax+bu, \tag{1}$$

where

$$A=-\begin{bmatrix} T_3T_4 & T_4(T_1-T_3) & -T_1T_4 \\ 0 & T_2T_4 & -T_2T_4 \\ 0 & 0 & T_2T_3 \end{bmatrix} / T_2T_3T_4,$$

$$b=\begin{bmatrix}0 & 0 & 1/T_4\end{bmatrix}^T, x=\begin{bmatrix}x_1 & x_2 & x_3\end{bmatrix}^T \in R^3,$$

u is the output of the controller, T_1, T_2, T_3 and T_4 are time constants determined according to identification, the regulated output and the protected output are

$$\begin{aligned} y_1 &= C_1 x, \\ y_2 &= fC_2 x, \end{aligned} \tag{2}$$

where f is a constant feedback gain, and

$$C_1=\begin{bmatrix}0 & 1 & 0\end{bmatrix}, C_2=\begin{bmatrix}1 & 0 & 0\end{bmatrix}.$$

The control objective is to design control strategy to make

$$\lim_{t\to\infty}\left|y_{r1}-y_1(t)\right|=0, \tag{3}$$

$$y_2(t)<y_{boundary}, \forall t, \tag{4}$$

where y_{r1} is a constant reference signal, and $y_{boundary}$ is the constant safety boundary for the temperature y_2. In the paper, it is assumed that $y_{r1}<y_{r2}/f$, which stands for that the tracking task does not destroy the safety boundary and the desired equilibrium point of the closed loop is in the safety region.

Usually, it is more practical to think about the safety with some margin than only to consider the critical safety. In this paper, the safety margin γ is defined as followed:

$$\gamma \overset{def}{=} \frac{y_{boundary}-y_2}{y_{boundary}}. \tag{5}$$

It is supposed in this paper that $y_{boundary}>0$, and $0<\gamma<1$ implies that the system is working in the safe region, and a larger γ stands for the safer status.

III. MAIN RESULTS

In this section, the command switching based strategy is adopted to solve the output regulation/safety protection control problem. The asymptotic tracking conditions are given, and the control parameters of the protecting controller could be optimized to minimize the ITAE performance index after the design of the regulation loop is finished.

A. Command Switching Control Based on Safety Margin

In this section, we try to modify the command switching control scheme mentioned in our previous work [8] to obtain better control performances. The modified controllers are directly illustrated as followed:

First of all, a full state dynamical feedback controller is employed instead of a PI controller in the regulation loop to make the poles of the closed loop arbitrarily assignable under the controllable condition:

$$u_1(t) = K_x x(t) + K_q q(t), \tag{6}$$

where $q(t) = \int_0^t (y_{r1} - y_1(\tau))d\tau$, and $\begin{bmatrix} K_x & K_q \end{bmatrix}$ is to be determined according to the desired poles.

The resulted closed loop equation of the regulation loop is

$$\dot{X} = A_{c1}(X - X_e), \tag{7}$$

where

$$X = [x^T, q]^T, A_{c1} = A_1 + B_1\begin{bmatrix} K_x & K_q \end{bmatrix},$$
$$X_e = -A_{c1}^{-1}\begin{bmatrix} 0_{3\times1} \\ y_{r1} \end{bmatrix}, A_1 = \begin{bmatrix} A & 0_{3\times1} \\ -C_1 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} b \\ 0 \end{bmatrix}.$$

Second, a proportional (P) controller is adopted in the protection loop to help the protected output escape from danger as soon as possible, as the same time, the output of the integrator q is set to vary more quickly during the protection interval than the regulation interval to improve the regulating performance:

$$\begin{aligned} &u_2(t) = K_p(Ly_{boundary} - y_2(t)), \\ &\dot{q}(t) = K(y_{r1} - y_1(t)), \sigma(t) = 2, \end{aligned} \tag{8}$$

where $L < 1, K > 1$ and K_p are constants to be designed. It can be known that when $y_1(t) < y_{r1}$, a quickly increasing q results in a quickly increasing positive control input, which helps $y_1(t)$ to reach y_{r1} quickly, and that when $y_1(t) > y_{r1}$, a quickly decreasing q brings a quickly decreasing negative control input, which helps $y_1(t)$ to reduce overshooting and to reduce times of switches. The corresponding equation of the protection loop is

$$\dot{X} = A_{c2}X + \xi_2, \tag{9}$$

where

$$A_{c2} = \begin{bmatrix} A - fK_p bC_2 & 0 \\ -KC_1 & 0 \end{bmatrix}, \xi_2 = \begin{bmatrix} Ly_b K_p b \\ Ky_{r1} \end{bmatrix}.$$

Third, the switching law is based on the safety margin to make the margin easy to estimate and is with hysteresis to better coin with practice, chattering also could be weakened due to the hysteresis:

$$u = u_{\sigma(t)}, \sigma(t) = \begin{cases} 1, \gamma > \gamma_{off}, \\ \sigma(t^-), \gamma_{on} < \gamma < \gamma_{off}, \\ 2, \gamma < \gamma_{on}, \end{cases} \tag{10}$$

where $0 < \gamma_{on} < \gamma_{off} < 1$ are constants to be designed. The switching law means that the protection loop will be switched on when the safety margin falls down to a given small number and will be switched off until the margin rises up to a sufficient large value. It is reasonable to assume that $\gamma(t_0) > \gamma_{off}$, which means that it is safe enough at the initial moment, so $\sigma(t_0) = 1$ .The asymptotic tracking conditions are proposed as followed:

Theorem1 Consider the system (1)-(2) controlled by the command switching controller (6), (8) and (10). Suppose that, there exists $t_1 > t_0$ such that for any $t > t_1$, we have $y_1(t) > y_{r1}$. If there exist a symmetric positive definite matrix R and a positive constant β satisfying

$$A_{c1}^T R + RA_{c1} \le -\beta I, \tag{11}$$

and the maximum value of the following quadratic programming problem (12) is non-positive, then the goal of asymptotic tracking (3) could be achieved:

$$\begin{aligned} \max \quad & (X - X_e)^T(A_{c2}^T R + RA_{c2})(X - X_e) \\ & + 2(A_{c2}X_e + \xi_2)R(X - X_e) \\ s.t. \quad & \begin{bmatrix} fC_2 & 0 \end{bmatrix} X \ge (1 - \gamma_{on})y_{boundary}, \\ & \begin{bmatrix} C_1 & 0 \end{bmatrix} X \ge y_{r1.} \end{aligned} \tag{12}$$

Proof: If the candidate Lyapunov function is selected as

$$V(X) = (X - X_e)^T R(X - X_e), \tag{13}$$

when $\sigma(t) = 2$, according to (9), we have

$$\begin{aligned} \dot{V} = &(X - X_e)^T(A_{c2}^T R + RA_{c2})(X - X_e) \\ &+ 2(A_{c2}X_e + \xi_2)R(X - X_e). \end{aligned} \tag{14}$$

It can be known from the condition (11) and (12) that $V(X)$ decreases in the whole time weather the regulation or the protection loop is switched on. The objective (3) can be thus realized. The proof is thus completed.

The quadratic programming problem (12) could be straightly solved using the optimal toolbox of Matlab. And the assumption of achievement of $y_1(t) > y_{r1}$ in finite time will be discussed combining with the simulations later.

Remark1 In common sense, the peak value which a given output of a fixed system could achieve is determined by the initial state. So the safety margin in the proposed frame of command switching control based on the safety margin can be estimated by the following nonlinear programming [9]:

$$\begin{aligned} &\max \quad fC_2[x_e + e^{A_2 t_m}(x_0 - x_e)] \\ &x_0, t_m s.t. \begin{cases} fC_2 x_0 = (1-\gamma_{on}) y_{boundary}, \\ fC_2 A_2 x_0 \geq 0, \\ fC_2 A_2 [x_e + e^{A_2 t_m}(x_0 - x_e)] = 0. \end{cases} \end{aligned} \tag{15}$$

where $x_0 \in R^3, t_m \in R^+$ are variables, and

$$A_2 = A - fK_p C_2 b, \; x_e = -Ly_b K_p A_2^{-1} b.$$

If the maximum value of (15) $y_m < y_{boundary}$, then we can easily get that $\gamma \geq \dfrac{y_{boundary} - y_m}{y_{boundary}}$.

Remark2 Suppose that $\{t_{oni}\}$ and $\{t_{offi}\}$ $i = 1, 2, \cdots$ stand for the instants when the protection loop is switched on and switched off respectively, and $\{y_{2\max i}\}$ is the series formed by the peak values which $y_2(t)$ could achieve from the initial state $X(t_{offi})$ during the regulation intervals. One conclusion lies in that if $\{y_{2\max i}\}$ declines strictly when $y_1(t) > y_{r1}$, then switching must happen finite times and the finally acted loop must be the regulation loop, and the asymptotic tracking is consequently achieved.

B. Optimation for the Control Parameters

The superiority of the multi-objective switching control schedule lies in that controllers corresponding to different goals could be designed separately. Take the command switching strategy proposed in this paper for an example, the control parameters of the protection loop, such as K, K_p and L are expected to be determined after the poles of the regulation loop are assigned. In other words, it is desirable that all the information of the regulation loop be available when the protected loop is under designing.

Under the asymptotic tracking condition, the three parameters mentioned above could be optimized by solving the following optimization problem:

$$\begin{aligned} &\min \quad J_{ITAE} \\ &K, K_p, L \; s.t. \; y_2(t) < y_{boundary}, \forall t, \end{aligned} \tag{16}$$

where the performance index is chosen as the famous Integral of Time-weighted Absolute Error (ITAE) index:

$$J_{ITAE} = \int_0^\infty \tau |e(\tau)| d\tau = \int_0^\infty \tau |y_{r1} - y_1(\tau)| d\tau. \tag{17}$$

The parameters minimizing J_{ITAE} of the closed-loop switched system (7)-(10) could be obtained by solving (16). With MATLAB, the powerful calculation tool, the optimization problem can be easily solved depending on pure numerical methods [10].

It is notable that if we can find a group of parameters corresponding to the minimum J_{ITAE}, then we have $J_{ITAE} < \infty$, and we have

$$\lim_{t \to \infty} t |y_{r1} - y_1(t)| = 0, \tag{18}$$

which implies the conclusion of asymptotic tracking.

C. Simulation Researches

According to the identification to the hypersonic air-breathing propulsion, the four time constants can be determined as followed:

$$T_1 = 0.4, T_2 = 0.15, T_3 = 0.3, T_4 = 0.15,$$

and we choose $y_{r1} = 1, \; f = 1$.

First of all, according to the rapidity requirement, we assign the poles of the regulation loop at $\lambda_{1,2,3,4} = -36$, resulted performance index is $J_{ITAE} = 0.0101$, and as is shown in Figure 2, the corresponding trajectory of the protected output $y_2(t)$ goes through the given safety boundary $y_{boundary} = 2$, which is not permissible for the safety demand.

The designing of the protection loop is thus necessary, and a group of permitted control parameters of the protection loop and that of the switching law are worked out according to the conditions in Theorem 1:

$$L = -19.5, K = 15, K_p = 20, \gamma_{on} = 0.1, \gamma_{off} = 0.11.$$

Figure 3 verifies the effectiveness of Theorem 1.

Moreover, the indices reflecting the performance can be obtained: controlled by the command switching controller, the maximum value of the protected output $y_2(t)$ is reduced to 1.9748, and the corresponding 2% error setting time of the regulated output $y_1(t)$ is $t_s = 0.4168s$, and $J_{ITAE} = 0.0122$.

It can also be seen from Figure 3 that when $y_1(t) < y_{r1}$, the output of the integrator q is an increasing positive variable no matter which loop is switched on, which makes $y_1(t)$ rise during the regulation intervals, and the regulated output will go through its reference signal since q increases even more quickly during the protection intervals according to (8). After the moment when $y_1(t) > y_{r1}$, during the regulation interval, the positive q will lead $y_1(t)$ to rise, and the declining of the candidate Lyapunov function depicted as condition (12) limits the falling amplitude of $y_1(t)$ during the protection interval, which makes the assumption of achievement of $y_1(t) > y_{r1}$ in finite time used in Theorem1 possible under proper parameters. The curve of the regulated output in Figure 3 could illustrate this assumption.

What can also be illustrated by Figure 3 is the condition of the strict decline of $\{y_{2\max i}\}$ when $y_1(t) > y_{r1}$, as is mentioned in Remark2. After the instant when $y_1(t) > y_{r1}$, the decreasing q leading to the decreasing control input may bring us the declining $\{y_{2\max i}\}$ as long as the positive feedback force during the protection interval is not quite large.

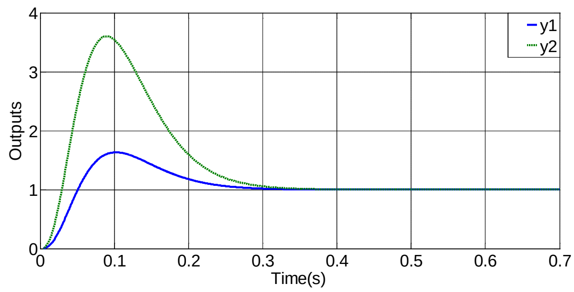

Figure 2. Curves of the regulated output and the protected output under single controller.

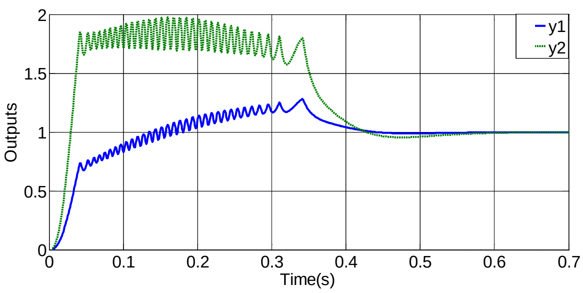

Figure 3. The improvement to the safety performance by the command switching control based on the safety margin.

Of course, replacing the poles of the closed loop nearer to the image axis could also reduce the peak value of the protected output $y_2(t)$, however, this will complicate the design procedure of the controller. And now we try to pull down the peak value of the protected output by replacing the poles in proportion, when the poles are assigned at $\lambda_{1,2,3,4} = -17.7$, as is shown in Figure 4, the peak value of $y_2(t)$ is 1.9911, and t_s is 0.5018s, $J_{ITAE} = 0.0287$.

It could be deduced that pulling down the peak value of $y_2(t)$ to a lower level will make the setting time of the regulated output even longer, which indicates the superiority of the proposed command switching strategy.

To get better performance, we choose

$$L = -19.5, K = 15, K_p = 20$$

as the initial value of the control parameters and solve the optimization problem (16) to search parameters which can minimize the performance index J_{ITAE} using the method introduced in [10], the obtained optimal control parameters are:

$$\begin{bmatrix} L & K & K_p \end{bmatrix} = \begin{bmatrix} -89.2672 & 61.7672 & 15.2793 \end{bmatrix},$$

the corresponding performance index is $J_{ITAE} = 0.0092$, and the curves are shown in Figure 5.

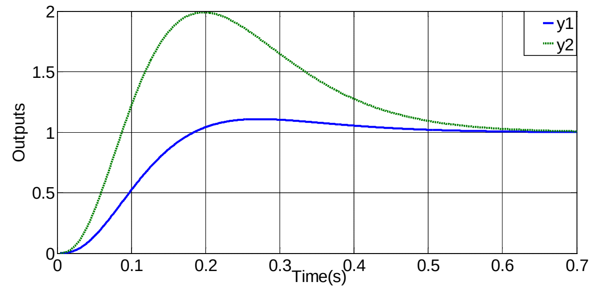

Figure 4. The improvement to the safety performance by replacing the poles of the closed loop nearer to the image axis.

It can be seen that under proper control parameters, the ITAE performance of a system using the command switching controller might be better than that of a system controlled by the single controller with the similar safety performance, and that under optimized control parameters, the ITAE performance of a system using the command switching controller could even be better than that of the single controller controlled system with the same regulation loop parameters (but without the permitted safety performances).

IV. Conclusions

This paper investigated the output regulation/ safety protection switching control problem for the simplified aeroengine model. Focusing on the safety boundaries existing during the working progressing, the command switching strategy based on the safety margin are adopted and the scheme mentioned in our previous work is modified in several aspects to get better performances. A dynamical state feedback

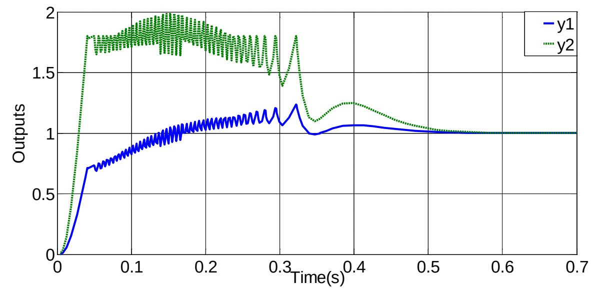

Figure 5. The improvement to the safety performance by the command switching control under the optimized control parameters.

controller and a proportional protection controller switch in a hysteresis way to balance the regulation and the safety demands. The principles guaranteeing the asymptotic tracking in a safe way asymptotic tracking are proposed. The control parameters could be calculated by solving optimal problems and could be optimized to obtain some best performance indices. Finally, simulation researches are performed to verify the effectiveness of the given results. It also can be indicated through simulation researches that the commands switching controller bring more improvement in both safety margin and the ITAE index than the single controller.

REFERENCES

[1] Rodriguez A., Dickeson J., Cifdaloz O., Kelkar A., Vogel J., Soloway D., Mc Cullen R., Benavides J., and Sridharan S., "Modeling and control of scramjet-powered hypersonic vehicles: challenges, trends, and tradeoffs," 2008, AIAA paper 2008-6793

[2] Z. H. Yao, W. Bao and J. T. Chang, "Modelling for couplings of an airframe - propulsion integrated hypersonic vehicle with engine safety boundaries," Proc. IMechE, Part G: J. Aerospace Engineering, 2010, 224(1): pp.43-55.

[3] Yu Daren, Liu Xiaofeng, "Multi-objective Robust Regulating and Protecting Control for Aero Engines. Journal of Engineering for Gas Turbines and Power," July 2008, Vol. 130.

[4] K. P. Tee, S. S. Ge, and E. H. Tay, "Barrier Lyapunov Functions for the control of output-constrained nonlinear systems," Automatica, 2009, vol. 45, no. 4, pp. 918-927.

[5] D. Liberzon, Switching in Systems and Control, Birkhauser, Boston, 2003.

[6] M. S. Branicky, Studies in hybrid systems: Modeling, analysis, and control, Ph.D. dissertation, Dept. of Electrical and Computer Engineering, Massachusetts Institute of Technology, 1995.

[7] Chen Chao, Yu Daren, Bao Wen, Zhao Jun, "Safety protection Switching Control for Aeroengines Based on Multiple Lyapunov Functions Method," Proceedings of the 29th Chinese Control Conference, 2010, pp. 5953-5957.

[8] Chao Chen, Daren Yu, Wen Bao, Jun Zhao, "Safety Protection Control for a Class of Linear Systems via Switching Strategy," Proceedings of the 30th Chinese Control Conference, 2011, pp. 1739-1744.

[9] Bertsekas D. P., Nonlinear Programming: Second Edition, Belmont, Massachusetts, Athena Scientific, 1999.

[10] Xue Dingyu, Computer Aided Control Systems Design Using Matlab Language (Second Edition), Tsinghua University Press, Beijing, 2006.