Surface-to-air Missile Autopilot Design Using LQG/LTR Gain Scheduling Method

YU Jianqiao*, LUO Guanchen, MEI Yuesong

School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

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Abstract

Linear quadratic Gaussian with loop transfer recovery (LQG/LTR) gain scheduling technique is utilized to design gain scheduling autopilot for surface-to-air missile. In order to eliminate the artificial uncertainties that the traditional “trial and error” design process introduces into system, a method to design target loop based on pole assignment is proposed, which provides an explicit algorithm to construct the matrix differential Riccati equation (MDRE) based on the expected poles determined by the performance specifications. Meanwhile, it is proved that by introducing integrators to augment plant dynamics the fast modes of LQG/LTR gain scheduling controller can be restrained effectively, which alleviates an obstacle for the engineering application of LQG/LTR gain scheduling technique. The proposed method is applied in the design of LQG/LTR gain scheduling autopilot for a surface-to-air missile. The design and simulation results indicate that the fast modes of controller are eliminated obviously, and that the dynamic characteristics of autopilot are stable when flight Mach number and altitude vary.

Keywords: gain scheduling; loop transfer recovery; pole assignment; autopilot design; flight control

1. Introduction

The dynamic characteristics of surface-to-air missile vary largely with flight Mach number and altitude. Therefore, gain scheduling technology is widely employed in surface-to-air missile control to design varying controller which can adjust parameters with respect to the variations of missile dynamics[1].

Gain scheduling technology is a controller design method dealing with widely varying, nonlinear and/or parameter-dependent dynamic system. Traditional gain scheduling approach developing a varying controller is to design several controllers based on selected points throughout the operating region and connect them with some algorithm of blending or interpolation[1]. Despite its popularity in engineering applications, traditional gain scheduling approach has obvious drawbacks because of the lack of rigorous theoretical basis. Even though the local point designs may have excellent robustness and performance properties, the global gain scheduling design need not have any of these properties[1-2]. This means traditional gain scheduling approach cannot guarantee global robustness and performance properties of the system in theory. Rather, in practical application, such properties are inferred from extensive simulations and experiments afterwards.

Quasi linear parameter varying (quasi-LPV) approach which was developed at the end of the 20th century can solve the above problems effectively, and have been successfully applied to flight vehicle control problems[3-9]. Various design avenues based on quasi-LPV frame, especially the linear quadratic Gaussian with loop transfer recovery (LQG/LTR) gain scheduling technique[6-8], have attracted considerable attention[9-11]. LQG/LTR gain scheduling controller is composed of a time-varying Kalman filter (TVKF) and a time-varying linear quadratic regular (TVLQR). TVKF loop can guarantee robustness and performance properties when parameters vary if controllability and ob-
servability conditions are satisfied\textsuperscript{[12]}. Therefore, by choosing TVKF as target loop, the gain scheduling controller designed by LTR technique can guarantee system global robustness and performance under parameter-varying conditions\textsuperscript{[13]}. The central work of applying LQG/LTR gain scheduling technique is to design the target TVKF loop. A matrix differential Riccati equation (MDRE) has to be constructed according to the given performance specifications in the target loop design. Usually, the MDRE is constructed through a “trial and error” process guided by the heuristic rules-of-thumb of the designer\textsuperscript{[14]}. This is a time-consuming process and, moreover, it is very hard to ensure that target loop dynamics is consistent at different points, which means that the smoothness of closed loop system dynamics cannot be guaranteed when parameters are varying. Meanwhile, the fast modes of LQG/LTR gain scheduling controller also restrain the application of the LQG/LTR technique in practice. In this paper, a new controller design method is proposed to solve these problems.

2. Overview of LQG/LTR Gain Scheduling Approach

This section briefly outlines the main results for LQG/LTR gain scheduling approach.

LQG/LTR gain scheduling approach is applicable to the control system design for linear parameter varying (LPV) systems and nonlinear systems that can be described in quasi-LPV form\textsuperscript{[6-8]}. The LQG/LTR gain scheduling control structure is shown in Fig.1.

![Fig.1 LQG/LTR gain scheduling control system structure.](image)

In Fig.1, \( r \) denotes the reference signal, \( \dot{x} \) denotes the state of controller, \( K_i \) and \( K_f \) are the Kalman gain matrix and control matrix respectively, TVKF loop and TVLQR loop construct the gain scheduling controller together. \( G \) is the plant with state-space form:

\[
\begin{align*}
\dot{x} &= A(\sigma(t))x + B(\sigma(t))u \\
y &= C(\sigma(t))x
\end{align*}
\]  

where \( A(\sigma(t)) \in \mathbb{R}^{nxn} \), \( B(\sigma(t)) \in \mathbb{R}^{nxm} \), \( C(\sigma(t)) \in \mathbb{R}^{pxn} \), \( x \in \mathbb{R}^n \), \( u \in \mathbb{R}^m \), \( y \in \mathbb{R}^p \), \( \sigma(t) \) is time-varying parameter vector. If \( \sigma(t) \) is independent of state vector \( x \), \( G \) is an LPV system, otherwise, \( G \) is a quasi-LPV system. When it is assumed that \( \sigma(t) \) can independently vary on \( x \), the quasi-LPV system can be dealt with as an LPV system. Although such assumption would introduce some conservatism, the control problem of nonlinear system can be dealt with by linear method\textsuperscript{[4]}. In the LQG/LTR gain scheduling controller design, control matrix \( K_c \) is obtained by solving a matrix algebraic equation Eq.(2) in real time,

\[
K_c = p^{-1}B^T(\sigma(t))P_c
\]  

where \( 0<P_c \in \mathbb{R}^{nxn} \) is resolved via a matrix algebraic Riccati equation Eq.(3); in order to achieve loop transfer recovery, \( p \) should be set as a positive real number approaching to zero\textsuperscript{[12-13, 15-18]}.

\[
0 = P_cA(\sigma(t)) + A^T(\sigma(t))P_c + C^T(\sigma(t))C(\sigma(t)) - p^{-1}PB(\sigma(t))B^T(\sigma(t))P_c
\]

Kalman gain matrix \( K_i \) is obtained by resolving a matrix algebraic equation Eq.(4) in real time,

\[
K_i = q^{-1}(\sigma(t))P_cC^T(\sigma(t))
\]

where \( 0<P_c \in \mathbb{R}^{nxn} \) is obtained via an MDRE Eq.(5), \( q(\sigma(t)) \in \mathbb{R}^n \) and \( N(\sigma(t)) \in \mathbb{R}^{nxn} \) are “tuning parameters” to be designed.

\[
P_i = A(\sigma(t))P_i + P_iA^T(\sigma(t)) + N(\sigma(t))N^T(\sigma(t)) - q^{-1}(\sigma(t))P_cC^T(\sigma(t))C(\sigma(t))P_i
\]

Different from the LQG/LTR design under time-invariant conditions, \( K_i \) is determined by MDRE here, which is the precondition to guarantee TVKF loop good feedback properties under time-varying conditions\textsuperscript{[6]}. When LQG/LTR gain scheduling technique is applied, designer needs to choose several operating points throughout the working region first, and then determine \( q \) and \( N \) at every operating point according to the system performance specifications and plant dynamics. Based on this, \( q(\sigma(t)) \) and \( N(\sigma(t)) \) are constructed by function fitting or interpolating method.

In traditional design process, \( q \) and \( N \) are usually constructed dependently on the practical experience of designer. The same work has to be repeated at all of the selected operating points. This process not only is exhausting (especially for the construction of \( N \)), but also introduces additional artificial uncertainties into system design, which results in the fact that the smoothness of target loop dynamics between operating points is hardly guaranteed.

To solve the problem, this paper proposes a method to design the target TVKF loop based on pole assignment.

3. Target Loop Design with Pole Assignment

A pole assignment method to design TVKF loop is proposed in this section.

**Step 1** Locate poles of target loop according to system performance specifications.

**Step 2** Freeze time-varying parameters at each operating point and calculate Kalman gain matrix ac-
According to determined target loop poles.

Let plant's system matrix be $A_i$, output matrix be $C_i$, and Kalman gain matrix be $K_i$ at the $i$th operating point, the transfer function matrix of target loop is

$$L = -C_i[sI - (A_i - K_iC_i)]^{-1}K_i$$  \hspace{1cm} (6)

Suppose $(A_i, C_i)$ is observable, the eigenvalues of matrix $A_i - K_iC_i$ can be assigned arbitrarily. The algorithm to determine $K_i$ based on the given poles is as follows[19].

1. Construct a square matrix $F_i \in \mathbb{R}^{n \times n}$ with eigenvalues equal to the desired poles. The pole assignment problem can be described as to find $K_i$ such that $A_i - K_iC_i = T^{-1}FT$, where $T \in \mathbb{R}^{n \times n}$ is a nonsingular transform matrix.

2. Construct a matrix $H \in \mathbb{R}^{n \times n}$, such that $(F_i, H)$ is controllable. Solve matrix equation $T(A_i - K_iC_i)T^{-1}FT = HC_i$ to determine $T$. Note that $T$ should be nonsingular, otherwise, $H$ must be reconstructed.

3. Solve for $K_i$ by $K_i = T^{-1}HT$.

Remark 1 In this step, system time-varying characteristics are not considered when $K_i$ is calculated at operating points. Hence $K_i(\sigma(t))$ cannot be constructed by fitting or interpolating method directly from the set of $K_i$. Otherwise, the robustness and performance properties of TVKF loop under time-varying condition cannot be guaranteed[20].

Step 3 Choose the value of $q_i$ at each operating point and calculate matrix $N_i$. With time-varying parameters frozen, system is treated as time-invariant. So in this case, $N_i$ satisfies

$$0 = A_iP_i + P_iA_i^T - q_i^{-1}P_iC_iC_iP_i + N_iN_i^T$$  \hspace{1cm} (7)

$$K_i = q_i^{-1}P_iC_i^T$$  \hspace{1cm} (8)

It needs to solve a group of equations containing $0.5n(n+1)$ quadratic equations and $0.5n(n+1)$ unknown quantities to determine $N_i$ from Eqs.(7)-(8) directly. Practice indicates that for high-degree system (large $n$), it is very difficult to solve the group of equations above. Here we present an elimination method for single-input-single-output ($m=1$) situation.

Substituting Eq.(8) back into Eq.(7) gives

$$N_iN_i^T = q_iK_iK_i^T - A_iP_i - P_iA_i^T$$  \hspace{1cm} (9)

where

$$N_i = [n_1 \ n_2 \ \cdots \ \ n_m]^T$$  \hspace{1cm} (10)

Investigating

$$\tilde{N} = N_iN_i^T = [n_1 \ n_2 \ \cdots \ \ n_m]^T[n_1 \ n_2 \ \cdots \ \ n_m] =
\begin{bmatrix}
n_1 & n_1 & n_1 & \cdots & n_1 & n_1 \\
n_2 & n_2 & n_2 & \cdots & n_2 & n_2 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
n_m & n_m & n_m & \cdots & n_m & n_m
\end{bmatrix} =
\begin{bmatrix}
n_{11} & n_{12} & \cdots & \cdots & n_{1n} \\
n_{21} & n_{22} & \cdots & \cdots & n_{2n} \\
\vdots & \vdots & \ddots & \cdots & \vdots \\
n_{m1} & n_{m2} & \cdots & n_{mn}
\end{bmatrix}$$  \hspace{1cm} (11)

We find that the elements of symmetrical matrix $\tilde{N}$ satisfy the equality

$$\tilde{n}_{ij}^2 = \tilde{n}_{ii}\tilde{n}_{jj}$$  \hspace{1cm} (12)

Based on the equality relationship above, $0.5n(n+1)$ quadratic equations about $P_i$ are constructed from Eq.(9). Putting the equations obtained above together with the $nm$ equations about $P_i$ decided by Eq.(8), we can get a group of equations containing $0.5n(n+1) + nm - n$ quadratic equations and $0.5n(n+1)$ unknowns. Compared with the original group of equations, the number of unknowns and the number of equations are decreased by $nm$ and $n$ respectively in the new group of equations, which can alleviate the computational burden remarkably.

Once $P_i$ is determined, $N_i$ can be solved from Eq.(9).

Step 4 Form matrix function $N(\sigma(t))$.

In this step we construct $N(\sigma(t))$ by fitting method according to the obtained $N_i$ at operating points. If the dimension of $\sigma(t)$ is too high and the fitting operation is difficult, we can also establish the relationship between $N$ and $\sigma(t)$ by interpolating method.

Step 5 Calculate $K_i$ through Eq.(4) and MDRE Eq.(5) in real time.

We have finished the target loop construction with pole assignment method by now. The sensitivity of the solution of MDRE is estimable when the coefficient matrices are perturbed[21]. Besides, the solution of MDRE is monotonic and bounded, leading to the dynamic performance specifications being limited in a range[22]. Furthermore, it has been proved that “target loop guarantees stability and robustness properties for arbitrarily fast time-varying parameter trajectories”[6]. Hence, when the closed-loop system approximates target loop, it is stable and can demonstrate good properties. The simulations will illustrate these.

4. Limitation of Fast Controller Modes

LQG/LTR gain scheduling approach can deal with control problem of LPV/quasi-LPV systems very well. However, practical work indicates that there often exist fast modes in the controller designed by this approach. For surface-to-air missile control, the existence of fast modes in controller will put high demand on the capability of missile-borne computer system and sampling rate, and as a result, impair the real-time performance of control system[14, 23].

The reason why fast modes exist in LQG/LTR gain scheduling controller can be explained as follows.

From Fig.1, LQG/LTR gain scheduling controller's system matrix is

$$A_k = A - BK_k - K_kC$$  \hspace{1cm} (13)
whose eigenpolynomial is
\[
\lambda(s) = \det(sI_n - A + \frac{1}{s}BUC + K_c(C)) \
\]

According to LQG/LTR theory, as \( p \to 0 \), \( K_c \to p^{-1/2}UC \), where \( U \in \mathbb{R}^{m \times m} \) is an orthonormal matrix \([12,24]\). So we have
\[
\lambda(s) = \det(sI_n - A + p^{-1/2}BUC + K_c(C)) \
\]

Eq.(15) indicates that \( p^{-1/2} \) might result in “big poles” of controller when \( p \to 0 \).

In order to achieve practical engineering application, the fast modes of LQG/LTR gain scheduling controller must be limited. Indeed, many controllers designed by modern control methodologies face the same problem. For instance, in Ref.[25] the fast mode in robust gain scheduling controller was truncated directly to solve this problem. However, by performing Gramian-based model state balance reduction analysis, it is indicated that the fast mode is the last one which can be removed. Therefore, although the truncated controller is more practical to use, it ruins the robustness and performance properties of the system. Ref.[26] solves the fast mode problem of robust gain scheduling controller effectively by introducing robust pole placement technique into controller design. However, to use this approach it is necessary to describe the conditions of controller solution in linear matrix inequality (LMI) form. Obviously, this approach does not apply to our problem either. Ref.[27] constrains \( H_\infty \) controller fast mode remarkably by augmenting plant with an integrator. The integrator is used to augment the plant in the design process and is integrated with the designed controller to form the real controller used in practice. Analysis indicates that this approach is applicable to LQG/LTR gain scheduling controller design. The augmented control system structure is shown in Fig.2.

![Fig.2 Augmented control system structure.](image)

In Fig.2, \( \hat{x}_k \) denotes the state of the designed controller for augmented plant, \( \hat{K} \) the designed controller, \( K \) the real controller applied in practice and \( \hat{G} \) the augmented plant with state space representation
\[
\dot{x} = \hat{A}x + \hat{B}u \\
y = \hat{C}x 
\]

where the symbol “~” denotes the notion of augmented system, \( \hat{A}, \hat{B} \) and \( \hat{C} \) can be expressed as follows:

\[
\hat{A} = \begin{bmatrix} A & B \\ 0_{m \times n} & 0_{m \times m} \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} 0_{n \times m} \\ I_m \end{bmatrix}, \quad \hat{C} = \begin{bmatrix} C & 0_{n \times m} \end{bmatrix}
\]

Now analyze LQG/LTR gain scheduling controller poles when the plant is augmented with integrators. The eigenpolynomial of controller system matrix in Fig.2 is
\[
\hat{\lambda}(s) = \det(sI_{m+n} - \hat{A}_0) \\
\det(sI_{m+n} - \hat{A} + \hat{B}\hat{K}_c + \hat{K}_c(C)) \\
\det\left(sI_{m+n} - \begin{bmatrix} A & B \\ 0_{m \times n} & 0_{m \times m} \end{bmatrix} + \begin{bmatrix} 0_{n \times m} \\ I_m \end{bmatrix}\hat{K}_c + \hat{K}_c(C) + 0_{n \times m} \right)
\]

when \( \hat{p} \to 0 \), \( \hat{K}_c \to \hat{p}^{-1/2}\hat{U}\hat{C} \), Eq.(17) is rewritten as
\[
\hat{\lambda}(s) = \det\left(\begin{bmatrix} sI_n - A + \hat{K}_1C & -B \\ \hat{p}^{-1/2}\hat{U}\hat{C} + \hat{K}_2C & sI_m \end{bmatrix}\right) \\
\det(sI_m)\det(sI_n - A + \hat{K}_1C + s^{-1/2}B(p^{-1/2}\hat{U}\hat{C} + \hat{K}_2C)) = \\
s^{-m/2}\det(s^2I_n + s\hat{K}_1C - A) + B(p^{-1/2}\hat{U}\hat{C} + \hat{K}_2C) = \\
s^{-m/2}\det(s^2I_n + \hat{p}^{-1/2}\hat{B}\hat{U}\hat{C})
\]

In Eq.(18), \( \hat{K}_1 \in \mathbb{R}^{n \times m} \) and \( \hat{K}_2 \in \mathbb{R}^{m \times m} \) are the first \( n \) rows and last \( m \) rows of \( \hat{K} \) respectively.

Comparing Eq.(18) with Eq.(15), it is found that although there is still a large value \( \hat{p}^{-1/2} \) in the formula for pole calculation, the degree of \( s \) increases from first-order to second-order, which inevitably makes the magnitude of controller poles reduce remarkably.

Another benefit brought by augmenting integrators is to improve the system order-tracing ability at low frequency. The cost of the method is that plant dimension rises from \( n \) to \( n+m \), which increases computational burden in the controller design. Fortunately, the increase in plant dimension would not lead to computational difficulty by use of the elimination method presented in Section 3.

5. LQG/LTR Gain Scheduling Autopilot Design

In this section an LQG/LTR gain scheduling autopilot is designed for a surface-to-air missile using the methodology established in the previous sections.

5.1. Autopilot design

Surface-to-air missile dynamics is written in LPV form
\[
\begin{bmatrix} \dot{a}_y \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} Z_{a_y} & Z_{a_y} \\ M_{\phi} & M_{\phi} \end{bmatrix} \begin{bmatrix} a_y \\ \phi \end{bmatrix} + \begin{bmatrix} Z_{\phi} \\ M_{\phi} \end{bmatrix} \tau \]

where \( a_y \) is normal acceleration, \( \phi \) pitch rate and \( \tau \)
elevator deflection; dynamic coefficients $Z_{\alpha}$, $Z_{\dot{\alpha}}$, $Z_{\beta}$, $M_{\alpha}$, $M_{\dot{\alpha}}$ and $M_{\dot{\beta}}$ are nonlinear functions of flight Mach number $Ma$ and flight altitude $h$. The design envelope is chosen to be $Ma \in [1.8, 3.6]$, $h \in [500, 6000]$ m.

In the design, actuator dynamics is approximated by

$$A(s) = \frac{1}{s + 170}$$

(20)

First, the design structure depicted in Fig. 1 is adopted to design autopilot. According to the demand from guidance loop, target loop poles are selected as $s_1 = -170$, $s_{2,3} = 28 \pm 28.6i$.

Set $p=10^{-9}$ and design LQG/LTR gain scheduling autopilot using pole assignment method presented in Section 3. Investigating the poles of the obtained controller at the chosen operating points indicates that there is a pair of conjugated poles whose magnitude is over $1.3 \times 10^4$. For example, at the point of $Ma=2.0$ and $h=6000$ m, controller poles are

$$s_1 = -2873.6, \quad s_{2,3} = -9.864.8 \pm 10.071.2i$$

The magnitude of $s_2$ and $s_3$ is so large that the control law calculation cycle has to be set less than 0.03 ms to guarantee the system stability in simulations, which is obviously unacceptable in engineering application.

Next we use the augmented structure depicted in Fig. 2 to design LQG/LTR gain scheduling autopilot for the missile. In this case the plant is a fourth-order system containing actuator, missile dynamics and an integrator. Correspondingly, the target loop is also a fourth-order system, and its desired poles are chosen to be

$$s_1 = -170, \quad s_{2,3} = 28 \pm 28.6i, \quad s_4 = -30$$

Target loop is designed using pole assignment method with $p=10^{-9}$ as well. Examining controller poles at operating points demonstrates that the magnitudes of poles are not more than $1.2 \times 10^4$. For instance, also at the point of $Ma=2.0$ and $h=6000$ m, controller poles are

$$s_1 = 0$$
$$s_{2,3} = -302.2 \pm 823.3i$$
$$s_{4,5} = -873.8 \pm 402.5i$$

The results verify the effectiveness of the augmenting integrator to restrain fast modes of the LQG/LTR gain scheduling controller.

5.2. Simulations

Static simulations, dynamic simulations and comparing simulations are carried out to test the LQG/LTR gain scheduling autopilot designed by pole assignment method using integrator-augmented structure.

5.2.1. Static simulations

In this case the time-varying parameters $Ma$ and $h$ are frozen at fixed values for both the missile dynamics and the controller. The corners of the design envelope formed by the four combinations of minimum and maximum values of the parameters $Ma$ and $h$ are chosen to be operating conditions. Figs. 3-6 show the step responses of target loop and controlled missile at four selected operating points respectively.
The acceleration response curves show that the specifications in terms of gain and settling time of the controlled missile match that of target loop very well. The overshoot of the acceleration responses is less than 10%, and the rising time and settling time are less than 0.1 s and 0.3 s respectively, which can satisfy the design demand very well. From the simulation results shown above, we can see that the angle of attack curves are quite different under different flight conditions. The reason resulting in this phenomenon is that the system dynamics (e.g. the transfer coefficient from the angle of attack to the normal acceleration) varies with the parameters $Ma$ and $h$, therefore the angle of attack needs to be adjusted to guarantee the acceleration outputs remain the same on different flight conditions. The static simulations verify the stability and performance of the designed autopilot on parameter-frozen conditions.

5.2.2. Dynamic simulations

To check the autopilot performance under parameter-varying conditions, dynamic simulations are carried out. In the simulations we assume that the missile flight Mach number $Ma$ and the flight altitude $h$ are changing as shown in Fig.7. The assumption is made just for simulations and does not correspond to any realistic flight process. Fig.8 shows square wave responses of target loop and controlled missile while parameters $Ma$ and $h$ are varying.

The simulation results show that under the parame-
ter-varying conditions given in Fig.7, the controlled missile can recover target loop precisely and maintain stable with scarcely any steady-state error. The simulation results also show that in order to keep the acceleration output following the square wave signal as flight Mach number $Ma$ and flight altitude $h$ change, the angle of attack varies with the flight conditions. Dynamic simulations verify the effectiveness of the proposed method on the parameter-varying conditions.

5.2.3. Comparing simulations

In order to further illustrate the effectiveness of the proposed pole placement scheme, we have designed an LQG/LTR gain scheduling autopilot by using traditional “trial and error” method to construct the “tuning parameter matrix” $N$, and then comparing simulations are carried out.

Suppose the missile flight Mach number $Ma$ and the flight altitude $h$ are also changing as shown in Fig.7, comparing simulation results are shown in Figs.9-11.

It is clear that the responses of controlled systems designed via pole placement scheme and the “trial and error” process respectively are quite close to each other. However, as mentioned in the introduction, the design through “trial and error” is a very time-consuming process and, as the design process depends on the heuristic rules-of-thumb of the designer to a very big extent, it is very hard to ensure target loop dynamics constant at different points.

6. Conclusions

(1) The proposed target loop design method for the LQG/LTR gain scheduling technology based on pole assignment can effectively deal with the heavy workload in target loop design and the difficulties to guarantee the smoothness of target loop dynamic characteristics under parameter-varying conditions.

(2) The fast modes of LQG/LTR gain scheduling controller can be restrained effectively by introducing integrators to augment plant.

(3) A surface-to-air missile LQG/LTR gain scheduling autopilot is designed by the proposed approach, and the design and simulation results verify the power and effectiveness of the approach.

References


**Biography:**

**YU Jianqiao** Born in 1972, he received B.S., M.S. and Ph.D. degrees from Beijing Institute of Technology in 1994, 1997 and 2007 respectively, and now is an associate professor there. His main research interests are flight dynamics and control, flight vehicle system design and robust control. E-mail: jianqiao@bit.edu.cn