Extra-Atmospheric Aircraft Control System Design Based on Loop Shaping Method

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***Abstract*—A robust automatic flight control system is designed for an extra-atmospheric aircraft. The control systems consist of attitude control system used modified H-infinity loop shaping method and the navigation system used Modified Augmented Proportional Navigation (MAPN) guidance law. In the inner-loop design, using the H-infinity loop shaping method to transfer the transfer function matrix from the real system to the target system , which is a very useful way to solve the difficulties in choosing a proper weighting matrix in the loop shaping. In the outer-loop design, the MAPNG law is derived by adding the line-of-sight into the Augmented Proportional Navigation (APN) law in order to improve the observability of the system. Compared with the traditional method, the system using the new methods in control system design have a larger robust stability margin, the decoupling and the bandwidth of the system also improve a lot, the guidance accuracy and the miss distance accuracy is higher, furthermore, it reduces the complexity and blindness for the designer to find the proper weighting matrix. The simulation results proved the control performance of the unmanned aircraft system achieves a top level performance.**

Keywords—extra-atmospheric aircraft; control system; H-infinity loop shaping; augmented proportional navigation

I. INTRODUCTION

Extra-Atmospheric Aircraft has an enormous, yet untapped potential as steady platform for monitoring and collision on missile-target, the research and exploitation of which have become a hot spot at home and abroad in recent years. To improve control system performance, many researchers have devoted to the study of implementing more advanced control techniques to the extra-atmospheric aircraft.

Among these control methods, loop shaping, which was proposed by McFarlane and Glover [1], is a very sensible and appealing procedure for the design of robust multiple input multiple-output (MIMO) feedback controllers. It is a combination of loop shaping and robust stabilization.

Even though designers usually obtain good loop-shaping weights and controllers using their engineering insight and intuition, it is well recognized in the practicing community that the design of loop-shaping weights W1 and W2 to achieve a desired loop-shape is not always straightforward, especially for plants with strong cross-coupling [2]. This is because it is not always clear how each element in the weights affects the singular values of the looped system and the complexity of this relationship considerably increases when non-diagonal weights need to be used.

In order to overcome miss distance problems in the presence of large target maneuvers, several modifications in the form of a bias added to PN for target acceleration compensation are suggested. One form of modification is the well known augmented proportional navigation (APN), where the commanded acceleration is a linear function of target acceleration as well. The proportional navigation (PN) guidance law has been analyzed very extensively in the literature[3]-[8]. Most guidance schemes in the literature are based on the principle of PN whose logic is to null the LOS rate by making missile heading rate proportional to the LOS (line of sight) rate while closing in on range[9].Indeed, PN was shown to be optimal for linearized engagement equations in constant speed missile and static target intercept scenarios. However, its performance sharply degrades in the presence of rapidly maneuvering or fast moving targets.

In this paper, the attitude control system used modified H-infinity loop shaping method and the navigation system used modified augmented proportional navigation (MAPN) guidance law. In the inner-loop design, using the H-infinity loop shaping method to transfer the transfer function matrix from the real system to the target system , which is a very useful way to solve the difficulties in choosing a proper weighting matrix in the loop shaping. In the outer-loop design, the MAPNG law is derived by adding the line-of-sight into the Augmented Proportional Navigation (APN) law in order to improve the observability of the system. Compared with the traditional method, the system using the new methods in control system design have a larger robust stability margin, the decoupling and the bandwidth of the system also improve a lot, the guidance accuracy and the miss distance accuracy is higher, furthermore, it reduces the complexity and blindness for the designer to find the proper weighting matrix. The simulation results proved the control performance of the unmanned aircraft system achieves a top level performance.

II. Mathematical Model

The extra-atmospheric aircraft is shown in figure 1. The engine numberd in 5~10 is used for attitude control, and the 1~4 is the orbit control engine.

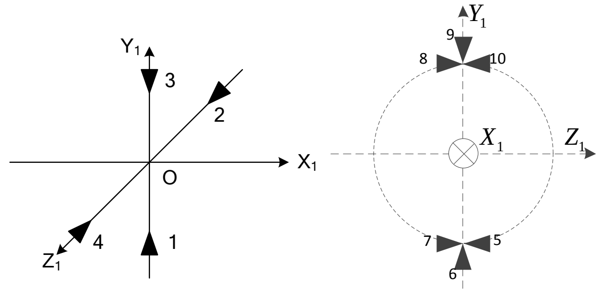

Fig. 1. Engine of attitude control and orbit control

III. Control System Design

The control system consist of attitude control system and orbit control system, the attitude control system used modified H-infinity loop shaping method and the navigation system used modified augmented proportional navigation (MAPN) guidance law. The control logic is designed for attitude control engine and orbit control engine with fixed thrust. The control system frame is shown in figure 2.

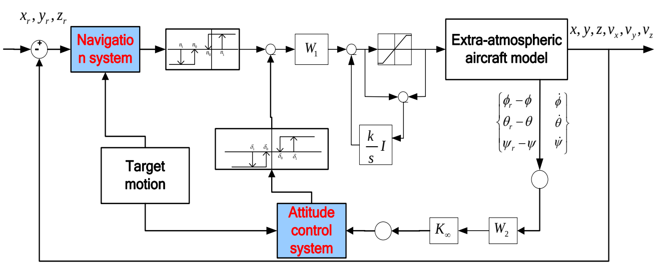

Fig 2. The control system frame of the extra-atmospheric aircraft

A. Attitude control system design

The H_∞ loop shaping method is used to design the inner-loop of the extra-atmospheric aircraft based on the model established and is described below [1].

Step 1. Let G denote a linear time-invariant model of the plant for which the controller is designed. Shape the singular values of G open loop with frequency-dependent weights W_1 andW_2 according to closed-loop objectives. The weighted plant $G_s = W_2GW_1$ is depicted in Figure 3. What follows is a typical weighting scheme. W_2 contains low-pass filters for noise rejection and lead-lag filters for improving robustness. W_1 contains proportional and integral (PI) filters. The integrators are used to boost the low frequency gain and thus improve output decoupling and tracking, and disturbance rejection at both the plant input and output. The proportional matrix gain is used to reduce the phase lag introduced by the integrators around crossover and to set the actuator usage. The overall gain of W_1 andW_2 is used to specify the desired loop bandwidth.

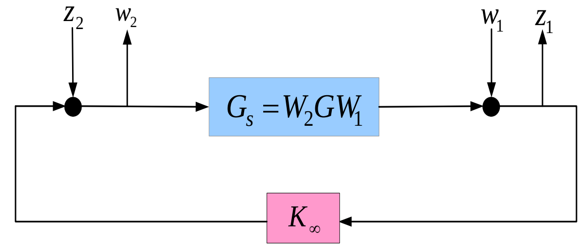

Fig. 3. The H_∞ loop-shaping standard block diagram

Step 2. Maximize the inverse of the H_∞-norm of the transfer matrix from disturbances $[w_1 \quad w_2]^T$ to errors $[z_1 \quad z_2]^T$ over all stabilizing controllers K_∞; that is,

$$\max_{stab K_\infty} \left\| \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \to \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \right\|^{-1} = \max_{stab\ K_\infty} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I - G_s K_\infty)^{-1} [I \quad G_s] \right\|_\infty^{-1} = \varepsilon \qquad (1)$$

The stability margin ε takes values in the interval [0, 1] and is a measure of robustness and performance. A margin greater than 0.3 is considered good, based on theory and practical experience. The theoretical basis for H_∞ loop shaping is that K_∞ does not modify the desired loop shape (Gs) significantly at low and high frequencies if the stability margin is not too small [1].

Step 3. Check time simulations and frequency responses of the resulting closed-loop system to verify robust performance. If not, then adjust the weighting matrix and recalculate K_∞ until closed-loop system achieve a good performance.

The simulation results are shown in Fig.3, noting that there consists coupling between different channels, the control inputs are added in three channels in the same time (pitch angle 15°, yaw angle 10°and roll angle 5°) , and the step responses are shown in figure 4.

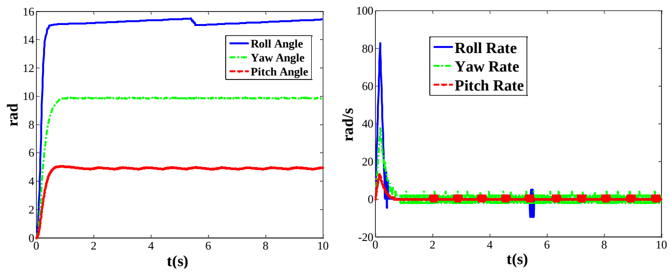

Fig 4. The step response of three channels

B. Navigation System Design

The equations of the target motion towards the extra-atmospheric aircraft is expressed in the target- line of sight frame[4]:

$$\begin{cases} \ddot{R} - R\left(\omega_{ys}^2 + \omega_{zs}^2\right) = -a_{xs} \\ R\dot{\omega}_{zs} + 2\dot{R}\omega_{zs} = -a_{ys} \\ R\dot{\omega}_{ys} + 2\dot{R}\omega_{ys} = a_{zs} \end{cases} \qquad (2)$$

The traditional PN guidance law has higher accuracy. But for highly maneuvering targets, the accuracy of traditional PN guidance law is still not enough. An APN guidance law is designed, an acceleration compensation of the target is introduced on the basis of PN guidance law to overcome the effect of the acceleration on the guidance accuracy. The structure of the APN is given by [10]：

$$a_{m_\beta} = NV_c\dot{\beta} + \frac{N}{2}a_{t_\beta} \qquad (3)$$

where, N is the navigation constant and a_{t_β} is the target acceleration information.

APN law is power and useful for maneuvering target, but it makes $\dot{\beta} \to 0$, the observability of the system becomes depressed， and the filter used to estimate the maneuvering target acceleration will be unconverged.

In order to improve the observability of the system, we derived the MAPNG law by adding the $kR\beta$ into the APN,

$$a_{m_\beta} = NV_c\dot{\beta} + \frac{N}{2}a_{t_\beta} + FR\beta \qquad (4)$$

From equation (4) we can see that the β and $\dot{\beta}$ will be oscillated in the terminal guidance, and the observability of the system is obviously improved. When $t \to t_f$, $kR\beta \to 0$, and the performance of the APNG and MAPNG law becomes similar.

The simulations are run for both using the PN method and APN method. The guidance methods are compared for two methods, and the simulations results are shown in Figure 5.

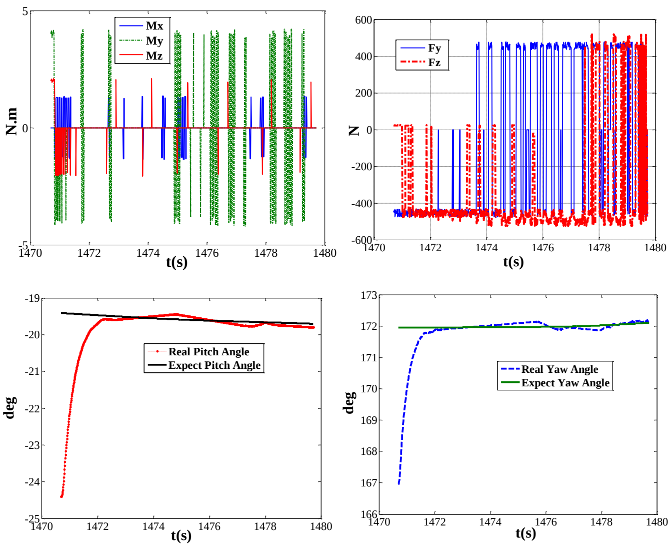

Fig 5. The result of the simulation

According to the results obtained, for homing against maneuverable targets, the MAPN guidance law is better than the PN guidance law in the following aspects： guidance accuracy is higher, miss distance is lower, interception time is shorter. And the new guidance law provides significant performance improvements over the commonly used classical proportional navigation law.

IV. SUMMARY

This paper designed a robust automatic flight control system for an extra-atmospheric aircraft based on H_∞ loop shaping method and MAPN guidance law.

1) The H_∞ loop shaping method is used to design the inner-loop in order to satisfy the requirements of decoupling and stabilization as well as the high bandwidth of the control system;
2) Using the loop shaping method to transfer the transfer function matrix from the real system to the target system in choosing a proper weighting matrix in the H_∞ loop shaping. Compared with the traditional method, the system using the new method have a larger robust stability margin, the decoupling and the bandwidth of the system also improve a lot;
3) The simulation results of the complicated trajectory tracking with the random wind disturbance show that the designed control system is very robust;
4) The MAPNG law is derived by adding the line-of-sight into the APN, the guidance accuracy and the miss distance accuracy is higher than the traditional method.

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