⊙ 研究論文

Atmospheric Re-entry Guidance and Control of Space Launch Vehicle

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우주 발사 비행체의 지구 재진입 유도제어

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초록

본 논문은 우주 발사 비행체가 지구 재진입 할 때의 유도제어에 관한 것이다.

우주 발사 비행체의 재진입궤적은 재진입 할 때의 특징에 따라 여러 단계로 나누어진다. 저항가속도는 각 단계에 따라 알맞은 파라메터로 표현되며, 해석적인 저항가속도로 단순화된 궤적으로 표현한다. 본 연구는 현재의 일반적인 궤적방법과 예측방법의 각각의 장점에 의한 혼합유도방법을 표현하였다. 제안된 유도방법을 이용한 우주 발사 비행체의 재진입 모의실험의 결과는 혼합유도방법이 지구대기 재진입 할 때 간단하고 효과적인 유도방법임을 보여주었다.

1. Introduction

Atmospheric reentry stage of manned spacecraft is a rather severe period, which needs delicate guidance and control.

Presently, nominal trajectory method and prediction method are generally used spacecraft reentry guidance methods[3].

The former uses a predesigned nominal trajectory that is kept unaltered throughout the atmospheric reentry[1][2]. The control law is simple and easy to be realized, but this method is vulnerable to initial condition dispersions and reentry disturbances, its landing point precision is relatively low. In the latter method, spacecraft dynamic differential equations should be successively solved by onboard computer; possible solutions based on real time state vector and flight parameters are provided for guidance and control; a trajectory which satisfies the reentry constraints and predicts the spacecraft reaching the predetermined landing point is selected for the next flight step. While the large amount of mathematical

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computations for guidance is a burden to the onboard computer, this kind of guidance has the advantages of insensitiveness to initial reentry condition dispersions, adapt-ability to various flight conditions and high precision of landing point control.

From the advantages and disadvantages of the above two methods, it is necessary to develope a simple and flexible guidance method of higher guidance precision. From this point, a new guidance method, what we called mixed guidance, that integrates the nominal trajectory method and prediction method is discussed here.

During a certain period of reentry, the flight of the spacecraft can be treated as flight along a certain type of trajectory. This is a typical reentry phase, that may be thermal protection phase, quasi-equilibrium glide phase, constant drag phase or etc., the complete trajectory can be formed by combining these phases together. Applying different simplification method to each phase, the drag acceleration equation of each phase can be written in fixed form and the reentry trajectory can be represented by corresponding parameters of these analytic equations. Various reentry constraints can also be written in the form of drag acceleration functions. Therefore, the manned spacecraft reentry trajectory is simplified into a piecewise parametric drag acceleration profile under reentry constraints which is the base of mixed guidance. Initial reentry trajectory may be found through parameter optimization. Using this drag acceleration profile as a reference trajectory, a real time trajectory control law can be formed for mixed guidance on the basis of nominal trajectory method . Since the acceleration profile is a piecewise analytic profile, all the variables in the guidance are analytic. The analytic functions are suitable to the reentry trajectory within a certain extent on the height and velocity plane of reentry, so the drag acceleration reference profile is not restricted to a given trajectory. It can be adjusted through parameter variations. The piecewise analytic drag acceleration profile enables analytic range prediction and the landing point dispersions can be predicted without enormous numerical computations, providing mixed guidance with the information for trajectory adjustment. Whenever the predicted landing point dispersion become too large because of reentry disturbances or nondesigned reentry conditions, the relative phases of reference drag acceleration profile are adjusted through parameter corrections. This is similar to the prediction method of guidance. After reference trajectory adjustment, the spacecraft is changed to be guided along the corrected reference trajectory by real time trajectory control law. Thus the mixed guidance method is achieved.

Mixed guidance is characterized by the analytic computations of all control gains and predictions, and it is also attractive in the ability of trajectory correction to deal with nondesigned reentry conditions.

Similar research has been done in America[6], while in this paper the concept of mixed guidance is defined, a new reentry reference trajectory and a new control law are suggested, finally simulation results based on engineering data are presented.

2. Spacecraft reentry trajectory design

2-1. Spacecraft dynamic equations

Considering that the earth rotation is relatively slow, Colias force experienced by the spacecraft can be omitted. Spacecraft dynamic equations in flight path coordinate system are as follows:

$$\dot{V}=-d-g\sin\gamma \tag{1}$$

$$V\dot{\gamma}=(\frac{V^2}{r}-g)\cos\gamma+l\cos\varphi \tag{2}$$

where g is gravity acceleration, *d*, *V* is drag acceleration and velocity.

Since during most part of reentry the flight path angle(γ) remains small, term ($g\sin\gamma$) which is relatively small compared with drag acceleration(d) can also be omitted, the dynamic equations are simplified as :

$$\dot{V}=-d$$

$$V\dot{\gamma}=\frac{V^2}{r}-g+(\frac{l}{d})_c d$$

where, V is used as independent variable; $(\frac{l}{d})_c$ is control variable, it is the component of lift to drag ratio in the vertical plane; drag acceleration (d) is function of velocity[5][6].

2-2 Atmospheric reentry corridor and simplified reentry trajectory

During the stage of atmospheric reentry, the spacecraft has to endure high overload of deceleration, aerodynamic heating and dynamic pressure. Safety reentry depends on the drag acceleration of spacecraft satisfying the above constraints. Atmospheric reentry corridor is defined on the plane of reentry drag acceleration and velocity.

The upper boundry is decided by the maximum overload($n_{\max}=4.5$g), maximum heating rate($q_{\max}=500$ (KW/s^2)) and maximum dynamic load($Q_{\max}=2.7\times10^4$(N/s^2)) that can be endured by the spacecraft, the lower boundary is formed by a no leap zero bank equilibrium glide.

According to the requirement of reentry corridor and the features of the reentry trajectory, the reentry drag acceleration profile describing the reentry trajectory is divided into different phases which are the simple functions of velocity. Five phases are included in the profile. They are two thermal protection phases, a quasi-equilibrium phase, a constant drag phase and a constant descending rate phase. The functions of drag acceleration to velocity of each phase are listed in Table 1.

Table 1. Piecewise Trajectory of Spacecraft Reentry

Flight Phase	Drag Acceleration
1. First Thermal Protection	$C_1(V_c-V)^2$
2. Second Thermal Protection	$C_2+C_3V+C_4V^2$
3. Quasi-equilibrium Glide	$\frac{g}{C_5}(1-\frac{V^2}{V^2_s})$
4. Constant Drag	C_6
5. Constant Desending Rate	$(\frac{d_i}{V^2_i}+\frac{C_7}{V_iH_s})V^2-\frac{C_7}{H_s}V$

In this table:

C_1-C_7: the adjustable parameters of reentry reference trajectory;

V_1-V_4: velocities at connection points between phases;

V_C: the initial reentry velocity;

V_S: the earth circle velocity;

H_S: the earth standard elevation(H_S=7.11 km).

2-3 Range Prediction

The piecewise analytic trajectory provides the ability of range prediction. Since

$$\dot{R}=V\cos\gamma \tag{3}$$

Combining equation (1) and (3), the following equation can be acquired:

$$R=-\int\frac{V\cos\gamma}{d-g\mathrm{sing}}dV \tag{4}$$

At the high velocity part of reentry, the flight path angle is so small that it can be assumed: $\cos\gamma=1$, $\sin\gamma=0$

So, equation (4) can be transformed into:

$$R=-\int\frac{V}{d}dV \tag{5}$$

As for the last phase of reentry in which the flight path angle varies to a large degree, the above simplification is not feasible. Since the value of drag acceleration is still large compared with $g\sin\gamma$, term $g\sin\gamma$ can be omitted in equation (4), range of the last phase can be predicted as:

$$R=-\int\frac{V\cos\gamma}{d}dV \tag{6}$$

Integrate equation (5) or (6), the range prediction functions of each phase can be derived, see table 2 for the results. Add up the predicted range of each phase, the range to the predetermined landing point can be calculated.

The predicted range of spacecraft during reentry can be computed from following function:

$$R_{predicted}=\begin{bmatrix} R_1(V)+R_2+R_3+R_4+R_5\ (V_0>V>V_1) \\ R_2(V)+R_3+R_4+R_5\ (V_1>V>V_2) \\ (R_3(V)+R_4+R_5\ (V_2>V>V_3)) \\ R_4(V)+R_5\ (V_3>V>V_4) \\ R_5\ (V_4>V>V_5) \end{bmatrix}$$

R_i is the predicted range of whole phase i. $R_i(V)$ is the predicted range from present to the end of phase i.

3. Guidance Logic and Control

3-1 Guidance logic

Mixed guidance is developed by assimilating the advantages of both nominal trajectory method and prediction method. In this guidance method, the real time trajectory control is

Table 2. Range Prediction of Each Reentry Phase

Flight Phase		Range Prediction
First Thermal Protection		$\frac{1}{C_1}\ln(\frac{V_c-V}{V_c-V_1})-\frac{V_c}{C_1}(\frac{1}{V_c-V}-\frac{1}{V_c-V_1})$
Second Thermal Protection $(Q=4C_2C_4-C_3^2)$	Q>0	$-(\frac{1}{2C_4}(\frac{C_2+C_3V_2+C_4V_2^2}{C_2+C_3V+C_4V^2})$ $+\frac{C_3}{C_4\sqrt{Q}}[\tan-1(\frac{2C_4V_2+C_3}{\sqrt{Q}})-\tan-1(\frac{2C_4V+C_3}{\sqrt{Q}})]$
	Q<0	$-(\frac{1}{2C_4}(\frac{C_2+C_3V_2+C_4V_2^2}{C_2+C_3V+C_4V^2})$ $+\frac{C_3}{2C_4\ \ -Q}\ln[(\frac{2C_4V_2+C_3-\sqrt{-Q}}{2C_4V_2+C_3+\sqrt{-Q}})/(\frac{2C_4V+C_3-\sqrt{-Q}}{2C_4V+C_3+\sqrt{-Q}})]$
Quasi-equilibrium Glide		$\frac{1}{2}-\frac{V_s^2-V^2}{d}\ln(\frac{V_s^2-V_3^2}{V_s^2-V^2})$
Constant Drag		$\frac{V^2-V_4^2}{2C_6}$
Constant Desending Rate		$\frac{1}{\frac{d_i}{V_i^2}+\frac{C_7}{H_sV_i}}\ln[\frac{\frac{D_i}{V_i}}{(\frac{D_i}{V_i^2}+\frac{C_7}{H_sV_i})V-\frac{C_7}{H_s}}]\cos\bar{\gamma}$

In this table :

d : drag acceleration when velocity is V;

γ : medium flight path angle of constant descending rate phase.

d_i, V_i : initial drag acceleration and velocity of constant descending rate phase;

acquired using nominal trajectory method, the landing point dispersion is predicted at the same time by analytic computations. Whenever the predicted landing point dispersion exceeds the maximum value or the predesigned landing point needs to be changed in emergence during flight, the guidance logic changes into trajectory correction in order to control the spacecraft to the predesigned landing point along a more precise trajectory.

3-2 Real Time Trajectory Control Law

Real time trajectory control law is used in mixed guidance to control the spacecraft to entry along a designed trajectory which satisfies the reentry constraints and landing point range requirement. According to nominal trajectory method, the control law is developed on the feedback information of drag acceleration, descending rate, velocity and range. Variable control gains are used in the control law to attain good dynamic response. System simplification and parameter substitutions are introduced for computing control gains. The reduced system is a fourth order system, the control law is :

$$\delta(\frac{L}{D})=f_1\delta\dot{d}+f_2\delta\dot{H}+f_3\delta V+f_4\delta R \qquad (7)$$

in which f_1-f_4 are new control gains. Matching the fourth order system to two second order system, when system frequency (ω) and damping coefficient(ξ) are set for each system, the functions for computing control gains are founded.

$$f_1=\frac{H_s}{d^2}[\omega^2_1+\omega^2_2+4\zeta_1\zeta_2\omega_1\omega_2+(\zeta_1\omega_1+2\zeta_2\omega_2)(\frac{\dot{d}}{d}-\frac{2d}{V}) \\ +\frac{2\dot{d}}{d}-\frac{\dot{d}^2}{d^2}+\frac{3\dot{d}}{V}+\frac{2d^2}{V^2}-\frac{d\dot{d}}{dV}-\frac{g}{H_s}(1-\frac{V^2}{gr})]$$

$$f_1=\frac{1}{d}[-2\zeta_1\omega_1-2\zeta_2\omega_2+\frac{3d}{V}-\frac{2\dot{d}}{d}] \qquad (8)$$

$$f_3=\frac{H_s}{d^2}[2\zeta_1\omega_1\omega_2^2+2\zeta_2\omega_2\omega_1^2-(2\zeta_1\omega_1+2\zeta_2\omega_2)\frac{d^2}{V^2} \\ +\frac{2dV}{Hs}-\frac{3d\dot{d}}{V^2}-\frac{5d^3}{V^3}-\frac{2d\dot{d}}{dV}]$$

$$f_4=-\frac{H_s}{d^2}\omega_1^2\omega_2^2$$

3-3 Trajectory Adjustment

Since the reentry trajectory is a piecewise analytic trajectory that is described by several parameters, it is easy to change the reentry trajectory to a new one by parameter adjustment when the predicted landing point dispersion exceeds maximum value. The trajectory is adjusted according to following principles.[5][6]

a) At the thermal protection phase of reentry, the trajectory is adjusted by shifting thermal protection phases and the quasi-equilibrium glide phase of trajectory up or down according to range requirement and reentry constraints, leaving the other phases of trajectory unchanged. Parameters that need correction are C_2, C_1, V_3.

Table 3. Parameter Adjustment of Reentry Trajectory

Flight Phase	Functions of parameter Adjustment
Thermal Protection	$C_2'=\frac{C_2-d(V_1)}{R_2+R_3}\Delta R$ $C_5'=C_5\frac{C_5}{R_2+R_3}\Delta R$ $V_3'=V_s\sqrt{1-\frac{C_5'C_6}{g}}$
Quasi-equilibrium Glide	$C_5'=C_5\frac{C_5}{R_2+R_3}\Delta R$ $V_3'=V_s\sqrt{1-\frac{C_5'C_6}{g}}\Delta R$
Constant Drag	$C_6'=\frac{V_2-V_4^2}{2(R_4-\Delta R)}\Delta R$
Constant Desending Rate	$C_7'=C_7\frac{V}{d\tan\gamma}\Delta R$

ΔR : the predicted landing point dispersion,
$\Delta R=R_{desired}-R_{predicted}$;
ΔR_i : the predicted range of phase i;
$d(V_1)$, d : drag acceleration

b) At quasi-equilibrium glide phase of reentry, just this phase of trajectory is shifted to eliminate the predicted landing point error, the constant drag and constant descending rate phase are not changed. Parameters for correction are C_5, V_3.

c) During the constant drag phase of reentry, only the constant drag value C_6 is adjusted to satisfied the range requirement.

d) Until during the last phase of reentry, the descending rate C_7 is modified.

Functions of parameter correction are in table 3. They are the results from following function:

$$C' = C + \frac{\partial R}{\partial d}\frac{\partial d}{\partial C}\Delta R$$

4. Simulation and Analysis

Spacecraft reentry is simulated by nominal trajectory guidance method and mixed guidance method. Comparisons of the landing point dispersions at typical reentry conditions are listed in table 4:

The reference reentry trajectory of mixed guidance and nominal trajectory method at various reentry conditions can be seen in Fig.1-Fig.4. The trajectory correction of mixed guidance is clearly shown in the figures.

In all the simulations, the nominal trajectory is used as initial reference trajectory of mixed guidance.

Fig.1 shows the reference trajectory of two guidance methods at nominal reentry conditions. Since the reference trajectory is the simplified analytic trajectory, it means that the design errors are unavoidable. The nominal trajectory method. causes a large landing point dispersion, whereas mixed guidance method, the trajectory design errors can be examined and corrected during the process of reentry, greatly reduced the landing point dispersion. It can be

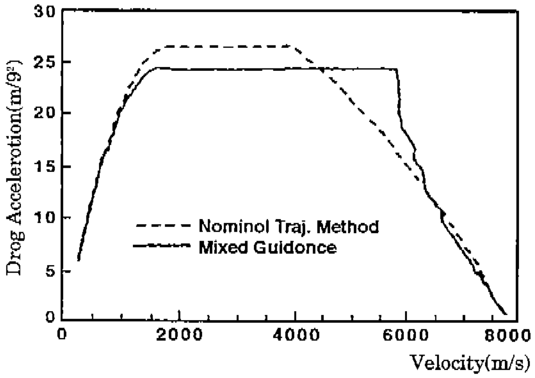

Fig 1. Reference Trajectory at nominal Reentry

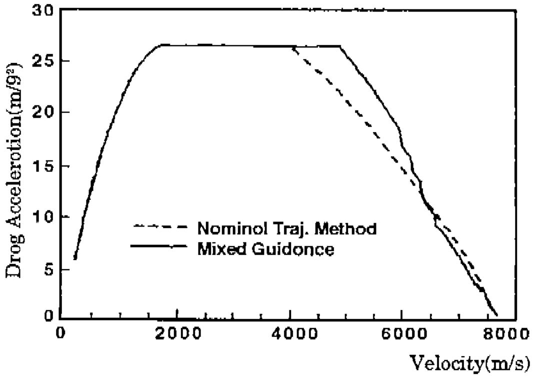

Fig 2. Reference Trajectory at break point dispersion

Table 4. Landing Point Dispersion

Reentry Condition	Nominal	1deg. Dispersion of Brake Point Position	2m/s Dispersion of Reentry Brake Impetus	1deg Manuver of Aimed Landing Point Latitude
Mixed Guidance	25.9	15.5	23.9	16.9
Nominal Trajectory Method	239.3	302.2	534.8	337.3
Ratio of Two Methods	10.8 %	5.0 %	4.5 %	5.0 %

seen from the figures that using mixed guidance method the reentry reference trajectory has been corrected from the initial one.

Fig.2 shows the reentry at one degree longitude dispersion from the nominal reentry break point position. Using nominal trajectory method without trajectory correction, this one degree dispersion of breakpoint causes a large dispersion of landing point. While using mixed guidance method the landing point dispersion can be predicted and reduced through trajectory correction, which can be seen from Fig.2.Fig.3 shows the reentry at 2m/s dispersion of break impetus. This causes large dispersion of reentry velocity and the angle of reentry. Since spacecraft reentry trajectory is vulnerable to these parameters small dispersions are enough to cause a very large landing point dispersion by nominal trajectory method. Mixed guidance eliminated these influences easily by range prediction and reference trajectory correction. Fig. 3 shows the corrected reference trajectory.

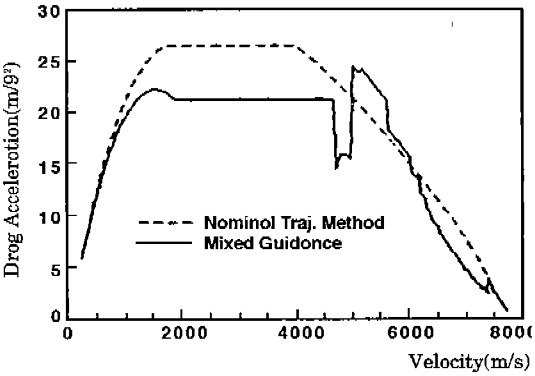

Fig 3. Reference Trajectory at break Impetus Dispersion

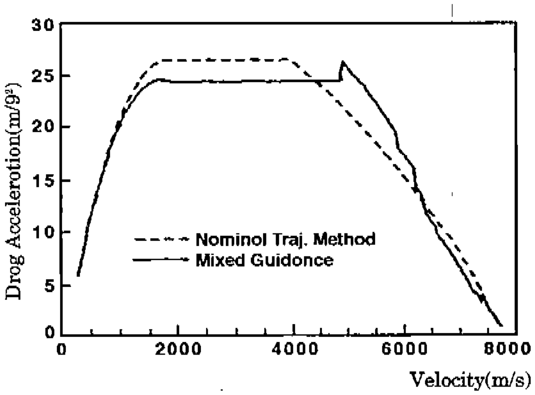

Fig 4. Reference Trajectory at landing point maneuver

Fig.4 shows the reentry at one degree maneuver of aimed points after the atmospheric reentry has started. Because nominal trajectory methods use a reference trajectory designed before reentry, it can not make up for the aimed landing point maneuver after the reentry begins, so a large landing point dispersion is expected. Since mixed guidance method can observe this maneuver and apply reference trajectory corrections timely, the spacecraft is guided to the new aimed landing point along the corrected reference trajectory, which is demonstrated in the figure.

It can be seen from table 4 that in all the above cases, mixed guidance has better performance than nominal trajectory method. Its landing point dispersion is only 5~11 percent of that of nominal trajectory method.

5. Conclusions

From simulation results, we can see that :

a) Using all analytic computations in mixed guidance, the guidance prediction efficiency is highly promoted.

b) Manned spacecraft can be safely guided to the aimed landing point without violating reentry constraints using piecewise analytic reentry trajectory in guidance and control.

c) Compared with the nominal trajectory method, mixed guidance has the advantage of higher control precision to the landing point, and it is more adaptable than nominal trajectory method at various reentry conditions.

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