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OF SPACE INTERCEPTORS

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CONTROL LAW OF TERMINAL-GUIDANCE SEGMENT OF SPACE INTERCEPTORS

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ABSTRACT: The article discusses the control law of space single-axis spin-stabilized interceptors, relying on multiple solid-fuel thruster engines for orbital control. By analyzing the motion law of the terminal-guidance segment with mathematical simulation, an effective divergence control method with proportional guidance is derived. Moreover, the authors go on to discuss the principle of selecting various control parameters, and measures for reducing the off-target amount, which have reference value in studying and developing similar types of space interceptors in China.

Key Words: space interceptors, proportional guidance, divergence control, orbital control, and off-target amount.

I. Introduction

As the pace of space competition for combat purposes intensifies with the development of modern defense technology, the leading military powers are competing in developing terminal-guidance space interceptors with high-level automatic homing, against missiles and satellites. This is the core of interceptor activity, with functions of automatic recognition, acquisition, and tracking of targets, as well as accurate guidance. The article studies the control law of mobile homing devices in the final segment of anti-satellite interceptors.

Solid-fuel thruster engines are used for orbital control in such interceptors. Arranged circumferentially, jetting nozzles are perpendicular to the axial line of the interceptor, and pass through its mass center. An infrared seeker senses the target information to be outputted to the seeker computer. The guidance control system accurately controls the thruster engines to fire at appropriate times, thus executing lateral mobile control.

During the final guidance flight segment, such interceptors apply the digital proportional-guidance law. With respect to flight vehicles traveling in the atmosphere, the normal-direction force required for correcting divergence is the continuous maneuvering force by deflecting aerodynamic surfaces. However, the maneuvering force studied in this paper is to control the object is the impulse-type divergence acting force. In the following analysis, it is to carry out proportional guidance as much as possible under the divergence control with respect to the design ignition law.

II. Setting up Mathematical Model

Since the control law of interceptors is the main subject of this study, in the preliminary analysis it is assumed that the orbital planes of the target and the interceptor are the same; both move in the same vertical plane. The derived control approach also has a certain significance as to interception in different orbital planes. Based on combat requirements, frontal attack is applied. Air drag is not calculated, because target and interceptor are both in exoatmospheric flight.

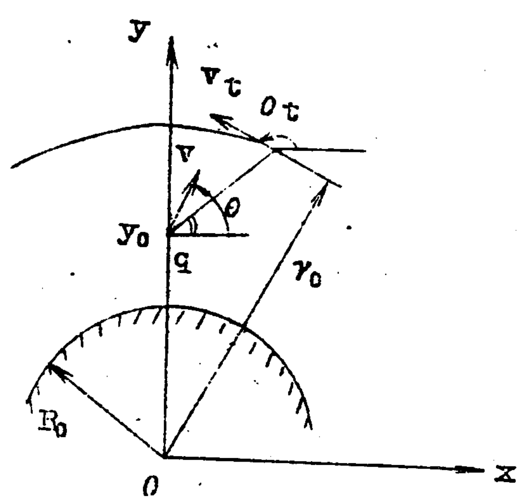

Fig. 1

(1) Equations describing the movement of the mass point within the vertical plane:

$$\begin{cases} dV/dt = -g\sin\theta \\ d\theta/dt = g(n_y - \cos\theta)/V \\ dx/dt = V\cos\theta \\ dy/dt = V\sin\theta \\ n_y = P/mg \\ dm/dt = -m_c \end{cases}$$

(2) Equations describing relative motion between interceptor and target

$$\begin{cases} dR/dt = -V\cos\eta + V_t\cos\eta_t \\ dq/dt = (V\sin\eta - V_t\sin\eta_t)/R \\ q = \theta + \eta \\ q = \theta_t + \eta_t \\ d\theta/dt = K \cdot dq/dt \end{cases}$$

Symbols in the equations stand for the following:

V - interceptor velocity

V_t - target velocity

θ - orbital dip angle of interceptor. Positive values indicate the counterclockwise direction of V-arrow starting from the X-axis

θ_t - is the orbital dip angle of target. Positive values indicate the counterclockwise direction of V-arrow starting from the X-axis

η - is the forward angle of the interceptor. Positive values indicate the counterclockwise direction of the line of sight from the V-arrow direction.

η_t - is the forward angle of the target. Positive values indicate the counterclockwise direction of the line of sight from the V_t-arrow direction.

m - interceptor mass

R is relative distance

q - angle of the line of sight.

With respect to the conventional guidance system, if the initial conditions are known and the necessary parameters are given, we can use the above-mentioned equations in mathematical simulation in obtaining the motion parameters of the interceptor. The digital proportional guidance law studied in this paper requires the concrete application and divergence of the control equation θ-dot=Kq-dot, before studying it.

III. Control Law

The control law of interceptors is to find an effective method of executing proportional guidance. This involves designing the engine firing law in order to satisfy the requirement that the number of engines is less than a given value, and that the off-target amount satisfies the technical requirement in achieving direct collision.

To study the key effect of divergent-type impulse control, factors of random interference, sensing errors, and system lag are not taken into account. These factors are considered only when analyzing accuracy.

3.1. Effect of gravity

The space interceptor flies outside the atmosphere, which is more than 400km in thickness. The external force acting on the interceptor, other than the maneuvering force, is only gravity. Therefore, the effect of gravity should be considered.

(1) Along the direction of flight-velocity

Based on calculation using the given data, due to the gravity effect the relative variation is very small (less than 0.03%) of the interceptor velocity within the control interval. The relative variation in the entire interception process is also less than 5%. Therefore, the effect of gravity along the velocity direction can be neglected with respect to a high-speed interceptor traveling at 2km/s. In other words, V is constant.

(2) Along the direction normal to the flight-velocity direction

Within the control interval, the impulse on the interceptor by gravity normal to the velocity direction is:

$$I_g = mg\cos\theta \cdot \Delta t \approx 21 \quad \text{(in Newton·second)}$$

(calculated by using θ=45° and Δt=0.1 second).

The impulse of a single engine is:

$$I_p \approx 35.76 \text{ (牛·秒)} \quad \text{(in Newton·second)}$$

If the spin effect of the interceptor is taken into account, the effective impulse will be further reduced. Apparently, I_g and I_p do not differ widely from each other; the variation amounts in direction of velocity due to these two quantities are of the same order of magnitude, therefore, the effect of gravity cannot be neglected in the direction normal to velocity.

3.2. Basis of control ignition

The terminal-guidance law of an interceptor is proportional guidance. The so-called proportional guidance law is as follows: in the process of the interceptor approaching the target, the control of the interceptor involves letting its rotational angular velocity of the velocity vector V-arrow in space be proportional to the rotational angular velocity q-dot of the target line-of-sight, thus, the rotational velocity of the line of sight approaches zero, to guide the interceptor flying toward the target. With respect to the infrared seeker, q-dot can also be easily obtained. Therefore, it is natural to consider applying q-dot to control engine firing in orbit.

The orbital-control solid-fuel thruster engine can be based on the requirements to simultaneously or continuously operate L such engines. The number L and the thrust direction are precisely controlled by the guidance control system. When studying the control law, the foregoing situation can be ideally carried out. To reduce the control energy loss and with the efficiency decreasing due to spin, it is better to use L engines in continuous operation.

In the proportional guidance automatic homing system, the target line of sight angular velocity (q-dot) is closely related to the off-target amount. Therefore, before selecting the control parameters, we should first understand the variation law of q-dot. Generally, the guidance procedure can be divided into three stages: transitional stage, tracking stage, and unstable-guidance stage. The main task of the control system in the transitional stage is to eliminate the initial error q_0-dot as rapidly as possible. The tracking stage involves mainly eliminating the tracking deviation q-dot, making it approach zero. The unstable-guidance stage is between loss of system stabilization and end of seeker operation. In this stage, q-dot is divergent. Thereafter, the interceptor is in an out-of-control stage.

Since the number of orbital control engines is definite, and since their capability of deviation correction is limited, the initial deviation q_0-dot cannot be too large. This is principally ensured by the guidance accuracy of the interceptor, and the predicted accuracy of sensing the target in orbit.

3.3. Selection of threshold value of $\underline{q}$-dot

To reduce the off-target amount, q-dot should be as small as possible when the seeker is out of control. if necessary, control should be stopped before q-dot begins diverging.

If the interceptor stops the control about 5km from the target, it is assumed that both the interceptor and target are traveling in straight lines after control stops. Based on the off-target amount calculation formula ([4] in references [not translated]) and the related data, to calculate it inversely with inverse calculation, the value of q-dot at the instant control is stopped should be smaller than 1.87×10^{-4}rad/s. This crude estimate can be used as the basis for selecting $\underline{q}$-dot. Therefore, the threshold value of $\underline{q}$-dot is, respectively, equal to

$$1.0 \times 10^{-3}\text{rad/s},\ 1.0 \times 10^{-4}\text{rad/s},\ 1.0 \times 10^{-5}\text{rad/s}$$

in the calculations. At each control, the number of engines fired is L, which is determined by the measured q-dot and threshold $\underline{q}$-dot:

$$L = |\mathrm{INT}(\dot{q}/\dot{\underline{q}})| \quad \text{(INT indicates integers are used)}$$

The control interval Δt is assumed to be 0.2s ,and each time the number of continuous firings is at most $L_m=4$. As an example, we cite the case that $\theta=31°$ is the initial condition. The simulation results indicate the following:

(1) By using q-dot as $1.0x10^{-3}$rad/s, the threshold value is too high. From the ignition control to t=12.6s, q-dot is consistently within the control range; engines are not fired. Due to accumulation of deviation, the firing conditions are satisfied when t=12.8s. Thereafter, notwithstanding that the maximum control force ($L=L_m$) is applied each time, a sudden increase in q-dot cannot be prevented; thus, the off-target amount exceeds the allowable range.

(2) It is relatively appropriate to use q-dot with the $1.0x10^{-4}$rad/s. Thus, not only is the number of engines the smallest, but also the off-target amount satisfies the requirements.

(3) The threshold value is too large when we take q-dot as $1.0x10^{-5}$rad/s. Although the off-target amount satisfies the requirements, too-early oscillations appear and the number of engines required is 50% more than under (2). This will lead to shrinking of the interception zone, and to higher accuracy of intermediate guidance being required. Moreover, the technical requirements of the seeker are higher if q-dot is too small.

As mentioned above, it is more rational to take the threshold value at $1.0x10^{-4}$.

3.4. Largest number of continuous ignitions (L_m) each time

At the initial state after starting control, to eliminate the initial deviation as early as possible, the value of L_m should be larger. However, considering the constraint of the control time interval and to avoid more complex control system, finally we take $L_m=4$ in the initial stage.

In the tracking stage and the divergence stage, since oscillations may be generated, to reduce the oscillation amplitude and to lower the dynamic error, we take $L_m=1$. From the result, if L_m is taken as 1 beginning at some instant in the tracking stage, thus, not only is the number of engines lower, but also the oscillations apparently are weaker.

3.5. Control time interval (Δt)

In the transition stage, since the distance is far and the value of L_m is taken to be large, Δt can be appropriately widened by taking Δt as 0.2 or 0.1s. After entering the tracking stage, to carry out rapidity and accuracy of control, Δt is appropriately shortened. However, Δt should be greater than the operating time ($\tau=0.012$s of each engine), therefore, the minimum Δt is taken as 0.02s.

3.6. Final determination of control parameters

After the foregoing analysis, the range of values for various parameters and their effects on off-target amount can be basically understood. On this basis, we can further study several feasible comprehensive parameters. With comprehensive consideration of calculations, the more suitable control law is determined as follows:

$t \leqq 12$ 秒[a]:	$\dot{q} = 5\times10^{-4}$ 弧度／秒[b],	Lm=4	$\Delta t = 0.1$ 秒[a]
$12 < t \leqq 14$ 秒[a]:	$\dot{q} = 1\times10^{-4}$ 弧度／秒[b],	Lm=2	$\Delta t = 0.05$ 秒[a]
$t > 14$ 秒[a]:	$\dot{q} = 1\times10^{-4}$ 弧度／秒[b],	Lm=1	$\Delta t = 0.02$ 秒[a]

KEY: a - second b - radians per second

The foregoing parameters determined are calculated in the intersection conditions. Basically, satisfactory results are obtained.

According to proportional guidance realized with the foregoing divergence control law, actually this is a type of proportional guidance of variable coefficients. Based on the dynamic equation and the control equation of an interceptor, there is

$V\dot{\theta} = LP/m$ (P is the thrust of a single engine, and

$\dot{\theta} = LP/mV = K\dot{q}$ L is the number of ignitions)

Therefore,

Since the value of L taken is related to q-dot, and since the relation is divergent, therefore the guidance ratio of K is variable; this is near-proportional guidance.

IV. Analysis of Guidance Accuracy

In the ideal situation, the motion of an interceptor in space obeys the proportional-guidance law. The control system attempts to point the interceptor at the instantaneous collision point. Actually, due to various interferences and system lags, there is an error angle Δq between the relative velocity vector and the line of sight of the interceptor and the target. After the final segment system of the interceptor is out of stabilization or control is stopped, the existence of Δq will finally generate the off-target amount.

4.1. Main Causes of Generating Off-target Amount

(1) Limitations due to the deviation-correcting capability of interceptor: Since the number of orbital control engines is limited, there is a higher requirement on the initial deviation when control commences. When the interceptor commences control, the effect of its direction of velocity θ_0 is the most serious to the off-target amount.

(2) Limitations on interceptor mobility: Since the number of continuous ignitions is 4 at most, with respect to the orbital control engines, the control at a certain point may be less than the required, thus the interceptor deviates from its datum orbit.

(3) Effect of divergence control: the impulse maneuvering force swings the direction of velocity around the ideal direction. Thus, the velocity vector of the interceptor relative to the target deviates from the target, thus leading to off-target status.

(4) Measurement error of q-dot: since the threshold value is in the order of magnitude of 10^{-4}rad/s, the requirements on measurement accuracy are very high.

(5) Effect of seeker in the control dead zone

4.2. Measures to reduce off-target amount

(1) The faster the action and the smaller the impulse of the orbital engine, the lower is the reciprocating swinging frequency of the interceptor, and the higher is the orbital accuracy that can be maintained.

(2) The engine ignition time, the threshold value of q-dot is paramount among the control parameters, directly affecting the control effect. With appropriate selection of the threshold value at the terminal stage, violent oscillations can be avoided, and the off-target amount can be reduced.

(3) To reduce the off-target amount, control should be halted before going out of control. It is appropriate to select the cease-control point at 4 or 5km.

(4) To reduce the effect of initial deviation q_0-dot when control begins, on the final off-target amount, we should ensure sufficient guidance accuracy of the carrier, and the predicted accuracy of target sensing.

V. Conclusions

The paper presents the interceptor ignition law to effectively carry out the proportional-guidance law with divergence control. The basis of selection of the control parameters, and the measures for reducing the off-target amount as presented in this paper can serve as reference material in developing similar kinds of interceptors. Although the provisional mathematical simulation indicates that direct collision can be carried out, yet the feasibility of direct collision should be thoroughly analyzed. The mathematical models of the seeker and the guidance control system should be introduced in further discussion.

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