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Guidance Technology of Horizontal Curved Flight for Short Range Aircraft with Inertial Navigation

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Abstract
For short-range aircraft with inertial navigation (called "fire and forget"), its flying time is short. Besides, the guidance technology is critical in initial introduction. Through mathematical modeling of the guidance technology in initial introduction, the guidance mechanism of aircraft's horizontal curve flight was studied in the work. Besides, simulations for flight control were conducted under different initial conditions. Results showed that it was feasible to imagine the line of sight to target in initial introduction. Furthermore, simulation results also provided critical technical basis for the comprehensive evaluation of aircraft's overall scheme and further study of aircraft system.
Keywords: AIRCRAFT; SHOULDER-TYPE SOFT FIRING; INERTIAL GUIDANCE; FLIGHT PATH SIMULATION; GUIDANCE IN INTRODUCTION

1. Introduction

For short-range aircraft with inertial navigation, called "fire and forget", its flying time is several seconds, with a flight distance of only hundreds of meters. Fig.(1) showed the launching process of shoulder-type aircraft with soft firing system. Once the target was found, shooter would activate the launching and controlling equipment. In the target tracking, the angular rate of line of sight to target was recorded by the launching and controlling equipment. Then, the average angular acceleration was calculated based on the 2s data of angular velocity[1][2][3][9][10][20].

Aircraft flight path was divided into straight and curve flight path depending on different projections of aircraft flight path. Straight flight path referred to ideal flight path with straight line on horizontal projection, while curve one to that with curve on horizontal projection. For the launching and controlling

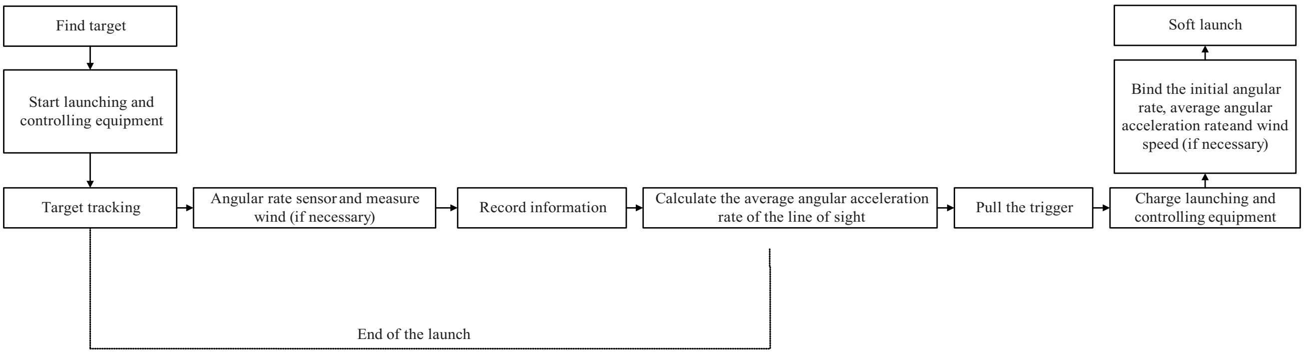

Figure 1. Launching and controlling program in setting and launching scheme of line of sight information

system of curve flight path, there was no need to calculate the horizontal advance angle before launching. Shooter directly launched aircraft when the target was aimed. Therefore, the launching and targeting time was short, without a high requirement for launching and controlling system[16][17][18][19].

In the work, mathematical modeling of guidance technology in initial introduction was used to study the control mechanism of guidance on horizontal and vertical plane. Besides, simulations for flight control were conducted under different initial conditions.

2. Research method

MGAERO was used to calculate aircraft's aerodynamic parameters. During the calculation, the specific aerodynamic parameters and structural quality of subsystems of aircraft were taken into account. In order to study the guidance technology in initial introduction, the uncontrolled flight path of aircraft leaving tube was calculated using the simulation of rigid body. Besides, controlled particle was also used to calculate the flight path of aircraft when control started.

Centroid and attitude motions of aircraft were described in the coordinate system of flight path and quasi-flying body coordinate, respectively. Such descriptions included the kinematic equations of simplified aircraft, kinematic equations of uncontrolled rigid body and controlled particle, and kinematic equations of aircraft with standard parameters[4][5][6][7][8].

2.1. Declination Law of Ideal Curved Flight Path

2.1.1. Guidance Law

The ideal curved flight path on horizontal plane was as follows (See Figure 2).

Supposing there was a horizontal line of sight from shooter to target, aircraft would hit the target as long as it flied along this line. Given rotation angular rate of aircraft's initial line of sight ω_{l0} and angular

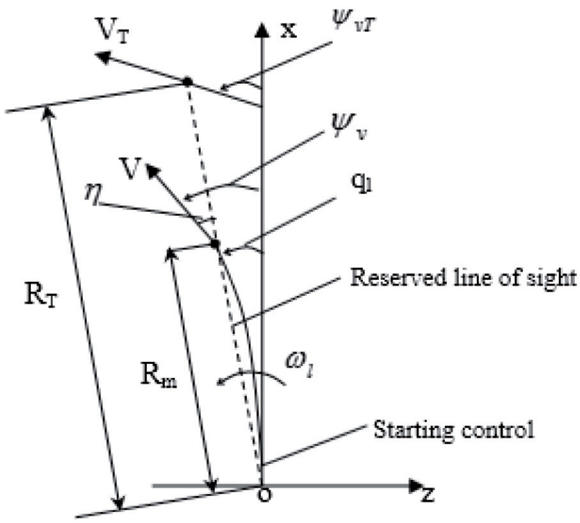

Figure 2. Ideal curved flight path on horizontal plane

acceleration ε_{l0}, with line of sight accelerating uniformly, horizontal angular velocity and angle were as follows.

$$\omega_l = \omega_{l0} + \varepsilon_{l0} t \tag{1}$$

$$q_l = \omega_{l0} t + \frac{1}{2}\varepsilon_{l0} t^2 \tag{2}$$

To make aircraft always in the line of sight, it is necessary to satisfy the following equations.

$$R_m \frac{dq_l}{dt} = V \sin\eta \tag{3}$$

$$\frac{dR_m}{dt} = V \cos\eta \tag{4}$$

$$\psi_v = q_l + \eta \tag{5}$$

Where $R_m, \eta, q_l, \omega_l, \varepsilon_l$ referred to aircraft's flying distance along the line of sight to target, angle between the direction of speed and line of sight to target, rotation angle of the line of sight to target, rotation angular velocity and acceleration of the line of sight to target, respectively.

2.1.2. Declination Law of Flight Path in Introduction

After launching aircraft, aircraft's direction of velocity and position cannot meet the requirements of guidance due to a short uncontrolled flight path. To complete the introduction of aircraft in the shortest time, it is assumed the introduction phase consisting of two arcs according to ideal introduction principle. Then, the aircraft will move regularly with the help of artificial control. Figure 3 showed the flight path in introduction.

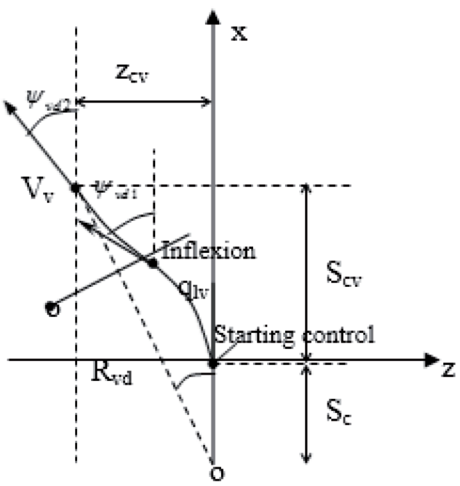

Figure 3. Flight path in introduction

(1) Introduction Distance and End Time

Given aircraft's introduction distance S_{cv}, the minimum effective range S_v, flight distance starting control S_c, flying rate starting control V_c, the moment starting control t_c, the moment introduced to inflection point t_{vg} and finishing introduction t_v, there are following equations when aircraft is accelerating uniformly.

$$S_{cv} = S_v - S_c \tag{6}$$

$$\frac{S_{cv}}{2} = V_c(t_{vg} - t_c) + \frac{1}{2}a_f(t_{vg} - t_c)^2 \tag{7}$$

$$S_{cv} = V_c(t_v - t_c) + \frac{1}{2}a_f(t_v - t_c)^2 \tag{8}$$

(2) Declination and Lateral Distance of Flight Path at the End of Introduction

At the end of introduction, aircraft's ideal declination of flight path was as follows.

$$\psi_{vd2} = \sin^{-1}(R_{mv}\omega_{lv} / V_v) + q_{lv} \tag{9}$$

Where R_{mv} referred to aircraft's flying distance along the line of sight to target at the end of introduction ($R_{mv} \approx S_v$); ω_{lv} the rotation angular velocity ($\omega_{lv} = \omega_{l0} + \varepsilon_{l0}t_v$); q_{lv} the rotation angle of sight to target at the end of introduction ($q_{lv} = \omega_{l0}t_v + \frac{1}{2}\varepsilon_{l0}{t_v}^2$); V_v aircraft's rate ($V_v = V_c + a_f(t_v - t_c)$).

In the whole process of introduction, the lateral moving distance of aircraft was as follows.

$$z_{cv} = S_v q_{lv} \tag{10}$$

(3) Ideal Introduction Radius and Declination of Flight Path at Inflection Point

The introduction radius was obtained by the iteration of following equation.

$$R_{vd} \approx S_{cv} / (\psi_{vd0} + 2\sqrt{\psi_{vd0}^2 / 2 + z_{cv} / R_{vd}}) \tag{11}$$

Where ψ_{vc} referred to the declination of flight path when aircraft was controlled, and ψ_{vd0} the declination difference between the end of introduction and start of control, namely $\psi_{vd0} = \psi_{vd2} - \psi_{vc}$.

$$\psi_{vd1} = c \cdot [\sin^{-1}(\frac{S_{cv}}{2R_{vd}}) + q_{lv}] \tag{12}$$

Where c referred to the correction coefficient when aircraft change its speed, determined by simulation.

(4) Declination Law of Flight Path in Introduction

The declination law of flight path in introduction was as follows.

$$\frac{d\psi_{v*}}{dt} = \begin{cases} \dfrac{\psi_{vd1} - \psi_{vc}}{t_{vg} - t_c} & t_c \le t < t_{vg} \\ \dfrac{\psi_{vd2} - \psi_{vd1}}{t_v - t_{vg}} & t_{vg} \le t < t_v \end{cases} \tag{13}$$

2.1.3. Declination Law of Flight Path in Introduction

(1) Information of Target's Relative Motion

According to Figure 3, the angular velocity of the line of sight to target was as follows.

$$\omega_l = \frac{V_T \sin(\psi_{vT} - q_l)}{R_T} \tag{14}$$

After derivation calculus, $\dot{R}_T / R_T$ was as follows for its little change with the conditions of $\varepsilon_l = \dot{\omega}_l$ and $\omega_l = \dot{q}_l$.

$$\frac{\dot{R}_T}{R_T} = -\frac{\varepsilon_{l0}}{2\omega_{l0}} \tag{15}$$

(2) Declination Law of Flight Path in Introduction

Aircraft being in the line of sight to target, the declination law of flight path in introduction was obtained when target moved uniformly.

$$\frac{d\psi_{v*}}{dt} = (2 + \frac{x}{V} \cdot \frac{\varepsilon_{l0}}{\omega_{l0}} - \frac{x}{V} \cdot \frac{\dot{V}}{V})\omega_l \tag{16}$$

Where ψ_{v*} referred to the ideal declination of flight path.

2.2. Ideal Yaw Angle and Acceleration Law of Z Axis[11][12][13][14][15]

Based on the wind measuring instrument in launching equipment, the ideal yaw angle and acceleration law of Z axis were induced when aircraft started control. Ideal yaw angle and acceleration of Z axis provided reference to the attitude control of yaw direction and position control of Z axis.

The following equations were obtained from the standard kinematic equation of aircraft with controlled particle.

$$F_{cz*} = \frac{m_y^{\beta} qSLmV\cos\theta_* \psi'_{v*} + (P\cos\alpha_* - C_z^{\beta} qS)M_{wy} + m_y^{\beta} qSLZ_w}{-P\cos\alpha_* L_c + C_z^{\beta} qSL_c - m_y^{\beta} qSL} \quad (17)$$

$$\beta_* = -\frac{F_{z*}L_c + M_{wy}}{m_y^{\beta} qSL} \quad (18)$$

$$\psi_* = \sin^{-1}(\sin\beta_* / \cos\theta_*) + \psi_{v*} \quad (19)$$

Of above equations, the symbols with asterisk on its superscript were ideal parameters.

3. Research results

3.1. Constraint Conditions in the Calculation of Flight Path

3.1.1. Step Calculation

To simulate the 1ms data exchange rate of aircraft computer, the step of flight path in calculation was assumed as $step = 0.001$.

3.1.2. Initial Setting

Supposing the initial target distance S_T, advancing speed V_{Tx} and transverse velocity V_{Tz}, the initial setting angular rate and acceleration rate were as follows for the launching and controlling program of curved flight path.

$$\omega_{l0} = \frac{V_{Tz}}{S_T} \quad (20)$$

$$\varepsilon_{l0} = -\frac{2\omega_{l0}V_{Tx}}{S_T} \quad (21)$$

3.1.3. Index of Flight

Only 0.2s after the launch of aircraft, the engine ignited and started control. The horizontal introduction distance of aircraft was 17m. When the aircraft flied to 65m, the maximum heights of aircraft's rectilinear and hedgehopping flight path were 0.5m and 2.5m, respectively. Approaching the target, the aircraft dropped 0.5m than from highest height.

3.1.4 Termination Condition

Given aircraft's horizontal distance x_m and target's horizontal distance x_T, the termination condition of simulation was as follows.

$$|x_m - x_T| \le 0.5 \quad (22)$$

3.2. Ideal Flight Path on Horizontal Plane

3.2.1. Ideal Curved Flight Path

Through simulation, the correction coefficient c =0.45 in introduction was determined. When the distance to target was 600m, and the lateral velocity of target changed from -15m/s to 15m/s without advancing velocity, the curved flight path, control, sideslip angle and overload curve of flight path were as follows. (See Figure 4-6)

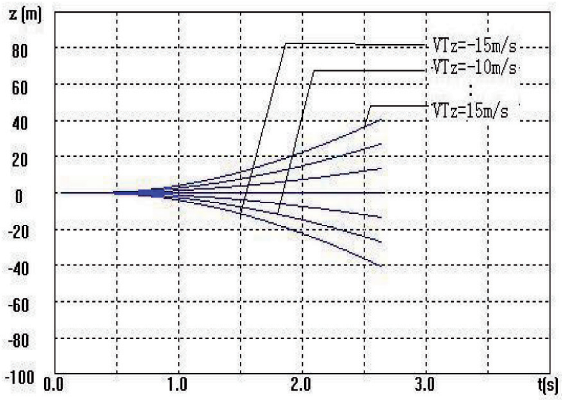

Figure 4. Horizontal curved flight path curve under different initial conditions

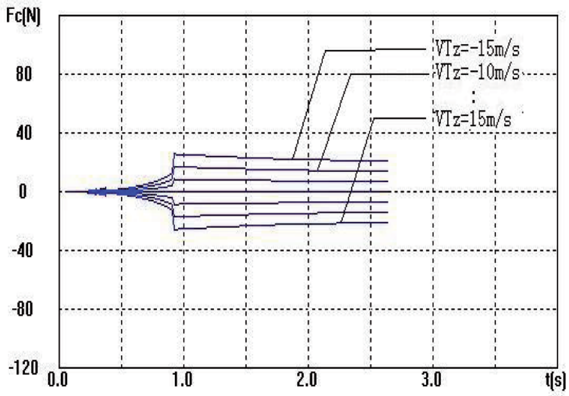

Figure 5. Control force curve on Z axis under different initial conditions

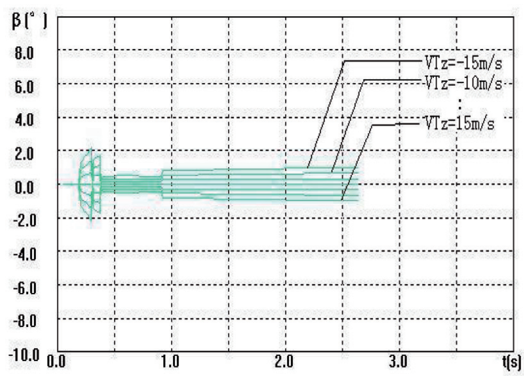

Figure 6. Sideslip angle curve under different initial conditions

Figures showed the flight path of aircraft was very flexuous while approaching the target with a large lateral velocity. Thus, aircraft should be limited to track target with lateral velocity less than 10m/s for the large overload required by aircraft, especially the one with large opposite movement. When the target was in the minimum effective range, the lateral speed of target tracked by aircraft should be less than 5m/s. Otherwise, the aircraft would stalled because the slip angle exceeded critical angle.

For the target in 50-600m area, the control force of aircraft should be less than the maximum control force provided by aircraft. Then, aircraft's slip angle was less than the critical angle. Therefore, aircraft can track the target under different conditions. At the end of acceleration, aircraft flied without motive power, thus needing the maximum control force. The flight overload of aircraft was provided by the wings, so aircraft had the maximum flight speed and stability with large control force.

4. Conclusions

Aircraft can track different targets under different initial conditions. Besides, the ideal flight path simulations were very accurate. Thus, it was feasible to carry out the target detection program for curved flight path, launching and controlling program and guidance method based on an imaginary line of sight to target. These programs satisfied the guidance requirements of short range aircraft with inertial navigation (also called "fire and forget").

Acknowledgements

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