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Synthesis of High-Precision Missile Homing System Using Proportional Guidance Method

Modern air targets are characterized by low visibility, high maneuverability and high survivability. In addition, for some specific targets, for instance ballistic missiles, in order to defeat them the missile need to be guided and carried out direct hit, i.e. "hit to kill". Therefore, in this paper, we present a high-precision missile homing system (MHS) using the proportional guidance method for firing at the highly maneuverable targets. Specifically, we propose a parametric optimization method for choosing a set of optimal parameters of the missile homing system for each dynamic parameter set of the missile. In addition, the paper gives the recommendations of choosing the initial conditions for the synthesis of missile homing system. In our experience, we should choose the small initial condition for synthesizing the missile homing system. Finally, the article also investigates the influence of systematic error in determining the speed, normal acceleration of missiles and the angular velocity of the line of sight of the missile and target on the accuracy of the missile homing system. We implement the proposed missile homing system and the parametric optimization method in Matlab. The experimental results illustrate that, using proposed system and the parametric optimization method, the missile can defeat the modern air targets with low visibility, high maneuverability and high survivability.

Keywords: *system synthesis, missile, missile homing system, proportional guidance method*

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Синтез высокоточной системы самонаведения ракеты с применением метода пропорционального наведения

Современные воздушные цели характеризуются малой заметностью, высокой маневренностью и высокой живучестью. Кроме того, для уничтожения некоторых конкретных целей, например боевых частей баллистических ракет, необходимо обеспечить прямое попадание, т. е. "hit to kill". Поэтому в настоящей работе представлена высокоточная система самонаведения ракеты с использованием пропорционального метода наведения для стрельбы по высокоманевренным целям. В частности, предложен метод параметрической оптимизации системы самонаведения ракеты для каждого динамического набора параметров ракеты. Кроме того, даны рекомендации по выбору начальных условий для синтеза системы самонаведения ракеты. По нашему опыту, мы должны выбрать малое начальное условие для синтеза системы самонаведения ракеты. Наконец, в статье также исследуется влияние систематической погрешности определения скорости, нормального ускорения ракеты и угловой скорости линии визирования ракеты и цели на точность работы системы самонаведения ракеты.

Мы реализуем предложенную систему самонаведения ракеты и метод параметрической оптимизации в среде Matlab. Результаты экспериментов показывают, что с помощью предложенной системы и метода параметрической оптимизации ракета способна поражать современные воздушные цели с низкой видимостью, высокой маневренностью и высокой живучестью.

Ключевые слова: *синтез системы, ракета, система самонаведения ракеты, пропорциональный метод наведения*

Introduction

Several missile homing systems (MHS) have been proposed in the recent years. These systems can be divided into two groups including: (1) classical methods and (2) modern methods. The first group consists of the chase method, chase method with anticipation, direct guidance method, direct guidance method with anticipation, proportional guidance method, parallel guidance method, etc. While the modern methods includes the proportional guidance method with offset, the proportional guidance method with anticipation and the homing method an instantaneous miss, etc.

For borby with air targets, thank to the high accuracy and simplicity of technical implementation, some of the classical method-based missile homing systems are widely used in recent years. As a result, a number of MHS systems have been developed for missiles using classical methods [1—9]. The chase method is not actually applied to the MHS, because it only allows the missile to attack from the rear hemisphere of the target. Whereas, the direct guidance method with anticipation is most often used in anti-ship missile systems, to combat low-speed targets. The parallel guidance method-based MHS system provides highest performance in term of accuracy. Because, when firing at a non-maneuverable target, the missile using this method has a straight trajectory, and the missile has a trajectory with a smallest curvature, when firing at a maneuverable target. However, due to the complexity of the technical implementation, it is not applied in the real-world environments [1, 2]. The proportional guidance method is widely utilized, because of the sufficiently high accuracy, all-foreshortening, all-height, and simple technical implementation [9]. It is noted that, there are two kinds of equation are used to present for this method. In the vertical plane [1, 3—8] the proportional guidance method is presented as flows:

$$\dot{\Theta} = k_p \dot{\varphi} \tag{1}$$

where, k_p is the proportional coefficient, φ is the angle of the line of sight of the missile and target, and Θ is the inclination angle of the trajectory of the missile. Whereas, in [9—12] the authors utilize Eq. 2 to present the proportional guidance method.

$$w = k_p v_a \dot{\varphi} \tag{2}$$

where, w is the normal acceleration of the missile, v_a is the approaching speed of the missile to the target. Multiplying the two sides of Eq. 1 by the velocity of the missile v, we get Eq. 3.

$$w = k_p v \dot{\varphi}. \tag{3}$$

As presented in Eq. 2 and Eq. 3, the difference between the two equations is v_a and v. To measure the value of v_a, a locator of range (radio or laser) is needed. Therefore, the homing system is complex, heavy and expensive. Whereas, although the value of v is difficult to measure, we can utilize its program value in our homing system. In other words, the using v_a is more complicated than v. Therefore, in this study we utilize Eq. 1 in the proportional guidance method. As a results, the law of the guidance is presented as follows:

$$\sigma_g = k(k_p \dot{\varphi} - \dot{\Theta}) \tag{4}$$

where, k is the coefficient, and k_p is the proportional coefficient. It is noted that, for the same values of k_p and $\dot{\varphi}$ when shooting towards the target, the system using equation (2) generates the normal acceleration greater than the system using equation (3). And when shooting in pursuit-less.

According to [9—12], in order to generate the control law σ_g, the coefficient k is not applied, and the value of k_{p} is choose in the range from 3 to 5. In addition, the authors in [9] also stated that, the MHS with such a small k_p value has large misses when shooting at highly maneuverable targets. Moreover, modern air targets are characterized by low visibility, high maneuverability, and high survivability. Therefore, to successfully combat them, it is necessary to improve the performance of the anti-aircraft missile systems. In [9], the authors describe a proportional guidance method with offset, which is necessary to determine the angular velocity of the line of sight of the missile-target without maneuvering targets, and increase in the angular velocity of the line of sight while maneuvering targets.

More recently, the modern method-based missile homing system, for instance the proportional guidance method with anticipation and the homing method on an instantaneous miss are described in [1, 2]. In this case, Eq. 5 are used to present the proportional guidance method with anticipation:

$$w_r = m(\tau) v (\omega_a + \omega_{n_x} + \omega_g + \omega_T) \tag{5}$$

where, w_r is the required acceleration of the missile; ω_a is the projection of the angular velocity of the line of sight on the antenna coordination system, proportional to the angular misalignment, measured by the homing head; The compensation components are calculated using on board computer including ω_{n_x} is the component, which compensates the longitudinal acceleration; ω_g is the component, which compensates the gravity; ω_T is the component, which compensates the maneuver of the target; and $m(\tau)$ is the coefficient of proportional navigation.

The equation represented the instantaneous miss homing method is illustrated as follows:

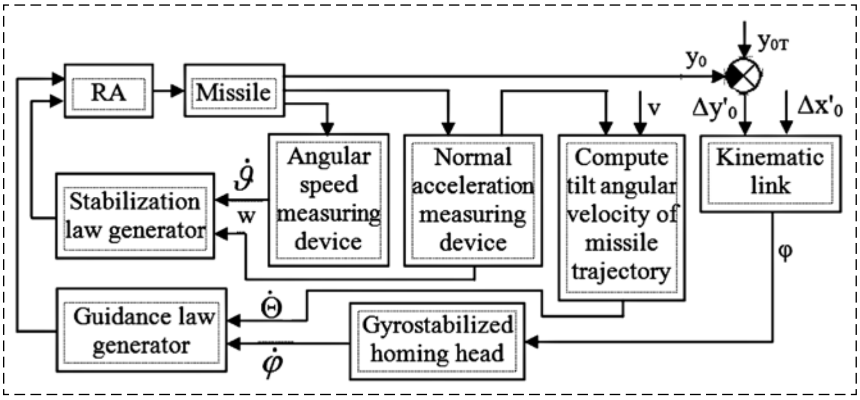

Fig. 1. The block diagram of the missile homing system

$$w_r = m(\tau)v\tau^2(\omega_a + \omega_{n_x} + \omega_g + \omega_T). \qquad (6)$$

As presented in Eqs. 5 and 6, the technical implementation of these methods is complex, requiring further the determination of the values of ω_a, ω_T. In addition, it is very difficult to estimate precisely the value of ω_T on the missile, because it requires the determination of the normal acceleration of the target [2], and is computed as follows:

$$\omega_T = \frac{\omega_{Tn}\cos q_T + \dot{V}\sin q_T}{2v}.$$

Therefore, the objective of this study is to develop a methodology for the synthesis of MHS using the proportional guidance method, and to give recommendations on the choice of initial conditions (the distance between the missile and the target at the begining time of the homing process) in the synthesis to improve its accuracy.

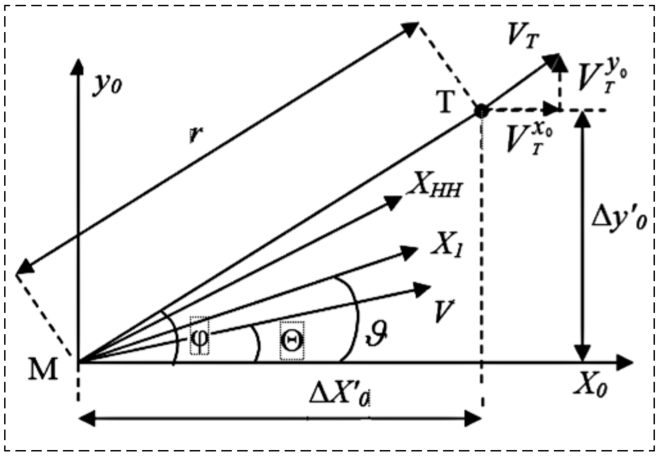

Fig. 2. The relative position of the missile and target

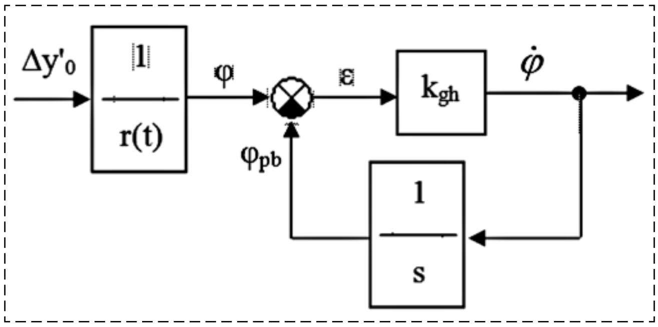

Fig. 3. Simplified scheme of gyrostabilized homing head

Mathematical model of the conventional missile homing system

The conventional block diagram of MHS with the application of the proportional guidance method in a vertical plane [8, 13] is presented in Fig. 1.

In order to implement the guidance method, the missile homing system consists of a rudder actuator (RA), angular speed measuring device (ASMD), normal acceleration measuring device (NAMD), compute tilt angular velocity of missile trajectory, gyrostabilized homing head (GHH), guidance law generator, stabilization law generator. The relative position of the missile and the target is shown in Fig. 2. A simplified scheme of GHH is presented in Fig. 3.

According to works presented in [3, 4, 8, 13], the mathematical model of the proportional guidance method-based MHS taking into account the dynamic properties of the measuring elements (RA in the first approximation is considered as an oscillatory link [1, 8], and the GHH is used) in the vertical plane is presented by a system of differential equations as follows:

$$\begin{cases} \dot{\omega}_{z1} = -a_{11}\omega_{z1} - a_{12}\alpha - a_{13}\delta; \\ \dot{\vartheta} = \omega_{z1}; \\ \dot{\Theta} = a_{42}\alpha; \\ \alpha = \vartheta - \Theta; \\ w = va_{42}\alpha; \end{cases} \qquad (7)$$

$$\begin{cases} \sigma_s = (k_w u_{ak} + k_{\omega z_1} u_g); \\ \sigma_g = k\left(k_p k_{gh}\varepsilon - \dfrac{w}{v}\right); \\ \dot{u}_{ak1} = \dfrac{k_{ak}}{T_{ak}^2} w - \dfrac{1}{T_{ak}^2} u_{ak} - \dfrac{2\xi_{ak}}{T_{ak}} u_{ak1}; \\ \dot{u}_{ak} = u_{ak1}; \end{cases} \quad (8)$$

$$\begin{cases} \dot{u}_{g1} = \dfrac{k_g}{T_g^2}\omega_{z_1} - \dfrac{1}{T_g^2} u_g - \dfrac{2\xi_g}{T_g} u_{g1}; \\ \dot{u}_g = u_{g1}; \\ u_r = \sigma_S - \sigma_g; \\ \dot{\delta}_1 = \dfrac{k_r}{T_r^2} u_r - \dfrac{1}{T_r^2}\delta - \dfrac{2\xi_r}{T_r}\delta_1; \\ \dot{\delta} = \delta_1; \end{cases} \quad (9)$$

$$\begin{cases} \varphi_{pb} = k_{gh}\varepsilon; \\ \varepsilon = \varphi - \varphi_{pb}; \\ \dot{x}_0 = v\cos\Theta; \\ \dot{y}_0 = v\sin\Theta; \end{cases} \quad (10)$$

$$\begin{cases} \dot{x}_{0T} = v_T \cos\Theta_T; \\ \dot{y}_{0T} = v_T \sin\Theta_T; \\ \Delta x_0' = x_{0T} - x_0; \\ \Delta y_0' = y_{0T} - y_0; \end{cases} \quad (11)$$

$$\begin{cases} r = \sqrt{\Delta x_0'^2 + \Delta y_0'^2}; \\ \varphi = 57,3\arcsin\dfrac{\Delta y_0'}{r}; \\ 0 \leqslant t \leqslant T^* \end{cases} \quad (12)$$

where, ω_{z1} is the angular velocity of the missile [degree/s]; α is the attack angle of the missile [degree]; δ is the angular velocity of rudder [degrees]; ϑ is the missile pitch angle [degree]; Θ is the inclination angle of the trajectory missile [degrees]; w is the normal acceleration of the missile [m/s^2]; v is the speed of the missile [m/s]; a_{11} is the natural damping coefficient [1/s]; a_{12} is the wind direction coefficient [1/s^2]; a_{13} is the rudder efficiency coefficient [1/s^2]; a_{42} is the normal force coefficient [1/s]; u_{ak} is output of the NAMD [v]; k_{ak}, ξ_{ak}, T_{ak} [s] are the conversion coefficient, damping coefficient, time constant NAMD, respectively; u_g is the output of ASMD [v]; k_g, ξ_g, T_g [s] are the conversion coefficient, damping coefficient, time constant ASMD, respectively; σ_s is the law of stabilization of normal acceleration; k_w is the feedback gain according to the normal acceleration; $k_{\omega z1}$ is the feedback gain for the speed of angular velocity; σ_g is the law of guidance; k is the coefficient; k_p is the proportional coefficient; u_r is the input of RA [v]; k_r, ξ_r, T_r [s] are the conversion coefficient, damping coefficient, time constant RA, respectively; φ is the inclination angle of the line of sight of missiles and targets [degree]; k_{gh} is the conversion coefficient of straight chain of GHH; x_0, y_0 are the coordinates of the missile on the horizontal and vertical axes [m]; x_{0T}, y_{0T} are the target coordinates on horizontal and vertical axes [m]; v_T is the target speed [m/s]; Θ_T is the inclination angle of the target trajectory; $\Delta x_0'$, $\Delta y_0'$ are the difference between the coordinates of the missile and target [m]; T^* is the guidance time [s].

Synthesis of missile homing system under different initial conditions

Based on the dynamic parameters (a_{11}, a_{12}, a_{13}, a_{42}) and the velocity v of the missile, it is necessary to select the parameters ($k_{\omega z1}$, k_w, k, k_p) to ensure the smallest guidance error. For the sake of simplicity of the synthesis process, the guidance error is determined by the distance between the missile and the target at the end of the homing process; the movement of the target is assumed to be rectilinear at a constant speed; the speed missiles is considered as constant; and the blindness of the homing head is skipped. The synthesis process of the MHS is carried out by parametric optimization in Matlab. We scan the parameters ($k_{\omega z1}$, k_w, k, k_p) in the range ($k_{\omega z1\min} \div k_{\omega z1\max}$, $k_{w\min} \div k_{w\max}$, $k_{\min} \div k_{\max}$, $k_{p\min} \div k_{p\max}$) with scanning step $dk_{\omega z1}$, dk_w, dk, dk_p, respectively. For each set of value ($k_{\omega z1}$, k_w, k, k_p) we integrate the systems using Eqs. 7—12 from the beginning to the end of the homing process to find the minimum of the guidance error. The optimal parameter set ($k_{\omega z1\mathrm{opt}}$, $k_{w\mathrm{opt}}$, k_{opt}, $k_{p\mathrm{opt}}$) is selected, if $k_{\omega z1\min} < k_{\omega z1\mathrm{opt}} < k_{\omega z1\max}$, $k_{w\min} < k_{w\mathrm{opt}} < k_{w\max}$, $k_{\min} < k_{\mathrm{opt}} < k_{\max}$, $k_{p\min} < k_{p\mathrm{opt}} < k_{p\max}$. Otherwise, we need to extend the scan range of the parameter set.

To reduce computational time, the following steps are carried out: Step 1 — We only integrate the system using Eqs. 7—12 when the values of parameters ($k_{\omega z1}$, k_w) providing the permissible stability margin of the stabilization circuit of the normal acceleration of the missile. In other words, the system satisfies the Hurwitz stability criterion and provide an oscillation index less than 1.7; Step 2 — From the beginning we do the pre-scan parameters ($k_{\omega z1}$, k_w, k, k_p) with a relatively "large" step ($dk_{\omega 1}$, dk_w, dk, dk_p). As a result, we get the rough "optimal" parameter set ($k'_{\omega z1}$, k'_w, k', k'_p). The optimal parameter set will be near this point; Step 3 — We scan the parameters ($k_{\omega z1}$, k_w, k, k_p) in the range ($k'_{\omega z1} - dk_\omega \div k'_{\omega z1} + dk_\omega$, $k'_w - dk_w \div k'_w + dk_w$, $k' - dk \div k' + dk$, $k'_p - dk_p \div k'_p + dk_p$) with a "smaller" step (dk_ω/N_1, dk_w/N_2, dk/N_3, dk_p/N_4), ($N_i > 5$) and integrate the systems using Eqs. 7—12 to find the real optimal parameters. The scanning step and the optimal parameters are selected when the guidance error is a few centimeters. Using such parametric optimization we can synthesize the MHS system on a personal laptop, built on the basis of the P6100 processor within 30 [s]. If we use a more modern laptop, built on the basis of an I5 or I7 processors, the synthesis time is even less.

According to [8], we assume a_{11} = 1,2 [1/s]; a_{12} = 20 [1/s^2]; a_{13} = 30 [1/s^2]; a_{42} = 1,5 [1/s]; v = 1300 [m/s]; k_r = 1 [degree/V]; ξ_r = 0,6; T_r = 0,05 [s]; $\delta_{max} = \pm 20$ degree; k_g = 1 [V/degree/s], ξ_g = 0,6, T_g = 0,05 [s]; k_{ak} = 1 [V/m/s^2], ξ_{ak} = 0,6, T_{ak} = 0,05 [s]; k_{gh} = 50; $k_{\omega z1}$ = 0,06÷0,4; k_w = 0,001÷0,01; k = 1÷20; k_p = 20÷100. The shooting is conducted towards. We conducted two experiments corresponding to two case study: Case 1 — Small initial condition, and Case 2 — Large initial condition.

In the Case 1, the initial condition are set to x_{0T} = 7000 [m], y_{0T} = 2000 [m], and v_T = 800 [m/s]. After implementation of the proposed parametric optimization in Matlab we get the optimal parameter set $k_{\omega z1}$ = 0,2; k_w = 0,002, k = 12, k_p = 45. As a result, the guidance error is 0.021[m] and the trajectory of the missile and the target are shown in Fig. 4.

We set the initial condition in the Case 2 are x_{0T} = 15 000 [m], y_{0T} = 5000 [m], and v_T = 800 [m/s]. The proposed MHS system provides the guidance error is 0,003[m], with the optimal parameter set is $k_{\omega z1}$ = 0,1; k_w = 0,001, k = 6, k_p = 59.

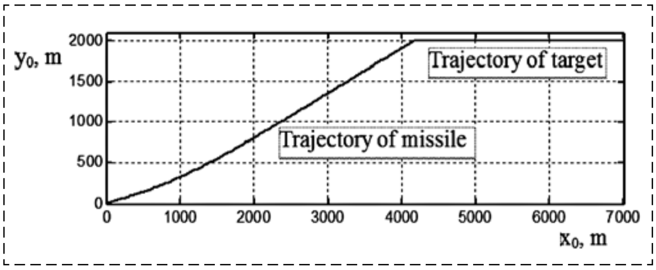

Fig. 4. The trajectories of missile and targets

It is noted that, the performance of the MHS depends on the initial conditions. Therefore, it is necessary to check the possibility of using the synthesized MHS in different initial conditions. The guidance errors for different initial conditions are given in Table 1.

As presented in Table 1, if we select a small initial condition the proposed parametric optimization of MHS generate a set of optimal parameter, which can be used in all other initial conditions of the homing process. Because, it provides small guidance error in all initial conditions. In addition, this also helps to reduce the computational time in the synthesis of the MHS. In contrast, if we choose a large initial condition for parametric optimization of MHS, we can get a set of optimal parameter, however this parameter set can not be used in all other initial conditions.

Study of the possibility of using the synthesized system for firing at highly maneuverable targets

In this section, we investigate the possibility of using synthesized MHS for firing at highly maneuverable targets. Assume that at the beginning of the guidance, the target has a coordinate x_{0T} = 15 000 [m], y_{0T} = 5000 [m] and the speed v_T = 800 [m/s]. Shooting is conducted towards. We conduct experiments with the acceleration of the target $w_T = -50$ [m/s^2], the optimal parameter set is $k_{\omega z1}$ = 0,2; k_w = 0,002, k = 12, k_p = 45, and the time t from the beginning homing process to the moment target start to maneuver, with t = 1s, 2s, 3s, 4s, 5s, 6s, or 6,2s. Guidance errors for different moments of time t are given in Table 2. The trajectories of the missile and the target with the homing time t = 2s are shown in Fig. 5.

As presented in Table 2, the homing time is t = 5s; t = 6s and t = 6.2s, the time from the beginning of the target maneuver to the end of the homing process is less than the transition time of the stabilization circuit of normal acceleration. There-

Table 1

V_T = 800 m/s										
x_{0T}, m	7000	7000	7000	7000	7000	12 000	12 000	12 000	15 000	15 000
y_{0T}, m	1000	2000	3000	4000	5000	5000	6000	7000	5000	6000
$k_{\omega z1}$ = 0,2; k_w = 0,002, k = 12, k_p = 45	0,316 m	0,021 m	0,507 m	0,087 m	0,01 m	0,004 m	0,004 m	0,007 m	0,002 m	0,009 m
$k_{\omega z1}$ = 0,1; k_w = 0,001, k = 6, k_p = 59	2,485 m	2,337 m	2,742 m	0,069 m	0,384 m	0,007 m	0,007 m	0,003 m	0,003 m	0,001 m

Table 2

x_{0T} = 15 000 m, y_{0T} = 5000 m, v_T = 800 m/s, w_T = −50 m/s^2								
t, s	1	2	3	4	5	5,5	6	6,2
$k_{\omega z1}$ = 0,2; k_w = 0,002, k = 12, k_p = 45	0,006 m	0,008 m	0,006 m	0,006 m	0,043 m	0,596 m	0,503 m	4,114 m
$k_{\omega z1}$ = 0,1; k_w = 0,001, k = 6, k_p = 59	0,0007 m	0,007 m	0,002 m	0,03 m	0,02 m	1,976 m	6,030 m	4,676 m

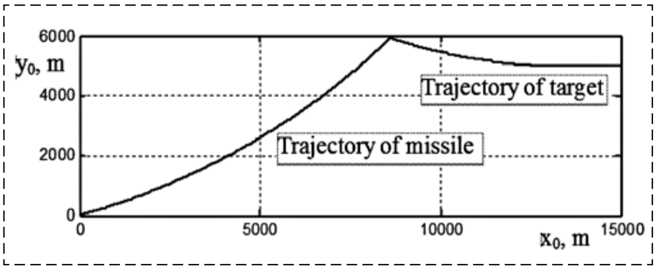

Fig. 5. Trajectories of missile and targets

fore, the guidance error increases dramatically. In contrast, if the time from the beginning of the target maneuver to the end of the homing process is greater than the transition time of the stabilization circuit of normal acceleration, the homing time is t = 1s, 2s, 3s, and 4s, then the accuracy of the MHS is ensured. As a results, the MHS obtained in the synthesis with a small initial condition is more accurate than the MHS obtained in the synthesis with a large initial condition.

Investigation of the influence of systematic error in determining inclination angular velocity of the missile trajectory on the accuracy of the missile homing system

Let us rewrite Eq. 4 as follows:

$$\sigma_g = k\left(k_p\dot{\varphi} - \frac{w}{v}\right). \tag{13}$$

As can be seen in Eq. 13, to generate the guidance law, it is necessary to determine the angular velocity of the line-of-sight missiles-target, the normal acceleration of the missile, and the missile speed v. The angular velocity of the line of sight of the missile-target is measured by GHH with sufficient accuracy. If we would like to improve its accuracy, the Kalman filter [1] can be applied. The normal acceleration of the missile is measured by a linear accelerometer. The speed of the missile could not be measured, thus we utilize the program value v_{prog}. We investigate simultaneously the influence of the systematic error of the linear accelerometer and the systematic error of determining the velocity of the missile on the accuracy of the MHS. In order to take into account the systematic error of the linear accelerometer and/or the difference between the program value and the real value of the missile speed, we propose an factor a. Then Eq. 13 is rewritten as follows:

$$\sigma_g = k\left(k_p\dot{\varphi} - a\frac{w}{v}\right). \tag{14}$$

Let us rewrite Eq. 14 as follows:

$$\sigma_g = ka\left(\frac{k_p}{a}\dot{\varphi} - \frac{w}{v}\right). \tag{15}$$

It can be seen that Eq. 15 and Eq. 13 has the same form, however the difference between them is that, there are new coefficient (ka) and a new proportional coefficient (k_p/a) in Eq. 15. We conduct experiments with the different values of the factor a, and the optimal parameter set is $k_{\omega z1}$ = 0,2; k_w = 0,002, k = 12, k_p = 45. The guidance error are given in Table 3.

As a result, the guidance error does not depend much on the systematic error of the linear accelerometer and the error of the program value of missile velocity (i.e., the accuracy of determining the inclination angular velocity of the trajectory of the missile).

Table 3

x_{0T} = 15000 m, y_{0T} = 5000 m, v_T = 800 m/s, w_T = −50 m/s^2, t = 2 s									
a	0,001	0,005	0,01	0,5	0,8	1	1,1	1,2	1,5
Guidance error, m	0,005	0,002	0,007	0,002	0,0008	0,008	0,0017	0,0036	0,002

Investigation of the influence of systematic error in determining the angular velocity of the line of sight of the target missile on the accuracy of the missile homing system

In equation 4, instead of using $\dot{\varphi}$ we utilize the measured value $\dot{\varphi}_m$. We assume that $\dot{\varphi}_m = b\dot{\varphi}$, therefore Eq. 4 can be rewritten as follows:

$$\sigma_g = k(k_p b\dot{\varphi} - \dot{\Theta}). \quad (16)$$

The form of Eq. 16 is the same as Eq. 4, however with a new proportional coefficient $k_p b$. We conduct experiments with the value of $k_p = 45$. The simulation results illustrate that, when $k_p b$ changes in the range from 17 to 104, the accuracy of the system is ensured.

Conclusion

In this paper, we have presented a high-precision missile homing system (MHS) using the proportional guidance method for firing at the highly maneuverable targets. Specifically, we propose a parametric optimization method for choosing a set of optimal parameters of the missile homing system for each dynamic parameter set of the missile. In addition, it is also advisable to choose a small distance between the missile and the target as an initial condition. Finally, the article also investigates the influence of systematic error in determining the speed, normal acceleration of missiles and the angular velocity of the line of sight of the missile and target on the accuracy of the missile homing system. The proposed missile homing system and the parametric optimization method are implemented in Matlab. The experimental results show that, missile equipped with our proposed system can defeat the modern air targets with low visibility, high maneuverability and high survivability.

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