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A Trajectory Prediction Method of Ship-to-air Missiles for Dynamic Firepower Compatibility

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Abstract

For the question of warship's air-defence firepower compatibility, a trajectory prediction method of ship-to-air missiles for dynamic firepower compatibility is put forward. Ship-to-air missiles' ideal trajectories are simulated based on targets' typical flight paths and missiles' guidance law, and missile's ideal position coordinates expression of time is obtained at the same time. Then trajectory distribution error sources which affect missiles' position coordinates are analysed. This method can predict trajectory efficiently before ship-to-air missiles' launch and help to avoid firepower interaction during warships' air-defence.

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Keywords: dynamic firepower compatibility; ship-to-air missile; trajectory simulation; three-dimensional trajectory

1. Introduction

Air-defence weapons on warships mainly include ship-to-air missiles, shipborne guns and jammings, which may affect each other when they are attacking aerial intimidators from different directions, different distances, and different altitudes at the same time. This is possible to lead to firepower interaction, which not only weakens attack efficiency, but also endangers own warship and sailors' safety. So it is necessary to make firepower compatibility judgement in air-defence missions. To judge whether the firepower is compatible or not, air-defence weapons' trajectories should be predicted based on targets'

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movement factors and typical paths and weapons' trajectories character before weapons are used, and this is called dynamic firepower compatibility. If more than two weapons' trajectories interact in time and space, only one of these weapons can be used, others should be put off. However, former researches on firepower compatibility are largely of static firepower compatibility [1-4].

Today, ship-to-air missile has been an important air-defence weapon on warships. The trajectories of ship-to-air missiles are related to targets' paths. When the target is maneuvering, ship-to-air missile also makes corresponding maneuver according to guidance law, which makes the trajectory of ship-to-air missile more complex, and makes trajectory prediction more difficult. In this essay, ship-to-air missiles' ideal trajectories are calculated by difference proportion guidance law in kinematics way, as a result, ship-to-air missiles' position coordinate expression of time is obtained. At last, trajectory distribution error from the error sources is analysed. So trajectory of ship-to-air missile can be predicted efficiently before the missile is launched.

2. Description of anti-ship missiles' end typical paths

The primary aerial menaces to warships are anti-ship missiles and battleplanes, of which the later is usually outside the range of ship-to-air missile. Anti-ship missiles have the character of high velocity and maneuverable penetration, and their end typical paths affect ship-to-air missiles' trajectories directly, so anti-ship missiles' end typical paths should be introduced.

There are four end typical paths of anti-ship missiles: (1) low elevation horizontal path; (2) snaky maneuvering path on the plane; (3) proportion guidance path on the plane; (4) zoom and then swoop down path. There are shown as figure 1.

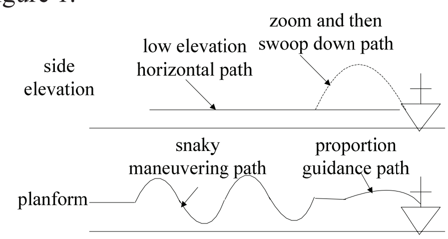

Fig.1 The illustration of end typical paths of anti-ship missiles

The front three typical paths are all possible in the range of ship-to-air missiles, and the target with the fourth path is usually too near to attack by ship-to-air missile, so ship-to-air missiles' trajectories corresponding to the front three typical paths were predicted.

3. Model and simulate ship-to-air missile's trajectory

3.1. Model of ship-to-air missile's trajectory

The guidance laws that ship-to-air missiles use include tracking law, proportion guidance law, and parallel approaching law and so on, of which the most common law is proportion guidance law. Proportion guidance law is that during missile's flight, rotational angle velocity of missile's velocity vector $\dot{\sigma}_m$ is proportional to rotational angle velocity of line between the missile and the target $\dot{q}_m$, namely $\dot{\sigma}_m = K \cdot \dot{q}_m$. K is the proportion guidance coefficient. Trajectory is calculated by difference proportion guidance method [5][6]. Because one step time Δt is short enough, the movements of missile and target are nearly beeline, there is shown as figure 2.

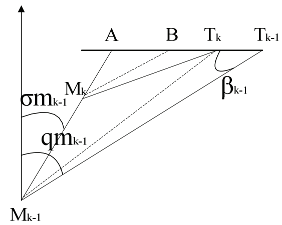

Fig. 2 The illustration of difference proportion guidance law

In figure 2, T_{k-1} and T_k represent target's position of the *k-1* and *k* step separately, and M_{k-1}、M_k represent missile's emended position of the *k-1* and *k* step, and qm_{k-1} represents the angle from line between missile and target to benchmark line of the *k-1* step, and σm_{k-1} represents the angle from velocity vector of missile to benchmark line of the *k-1* step. $T_{k-1}T_k$ and $M_{k-1}M_k$ intersect at A. Make M_kB parallel to $M_{k-1}T_{k-1}$ across M_k intersect $T_{k-1}A$ at B, $r(k-1)$ and $r(k)$ represent the distance between missile and target of the *k-1* and *k* step, v_m represents the velocity of ship-to-air missile, and v_t represents the velocity of target, s_m represents missile's movement distance $s_m = v_m \cdot \Delta t$ during one step Δt, s_t represents target's movement distance $s_t = v_t \cdot \Delta t$ during one step Δt. (x_m, y_m, z_m) is the position of the missile, and (x_t, y_t, z_t) is the position of the target, $(x_1(k), y_1(k), z_1(k))$ is the position of A.

Assumed that $M_{k-1}T_k = c$, $AM_{k-1} = c_1$, $AT_{k-1} = c_2$, $M_kT_k = c_3 = r(k)$, $\angle AM_{k-1}T_{k-1} = \alpha_{k-1}$, $\angle AM_kT_k = \alpha_k$, $\angle AT_{k-1}M_{k-1} = \beta_{k-1}$ and $\angle AT_kM_k = \beta_k$, of which $\beta_{k-1} = \angle AT_{k-1}M_{k-1} = \arccos(\frac{[r(k-1)]^2 + s_t^{\ 2} - c^2}{2r(k-1)\cdot s_t})$, so the position of A is as follows:

$$\begin{cases} q_k = q_{k-1} + \Delta q, \sigma_k = \sigma_{k-1} + k\Delta q, \alpha_k = q_k - \sigma_k \\ x_1(k) = x_t(k-1) + \frac{c_2}{s_t}(x_t(k) - x_t(k-1)) \\ y_1(k) = y_t(k-1) + \frac{c_2}{s_t}(y_t(k) - y_t(k-1)) \\ z_1(k) = z_t(k-1) + \frac{c_2}{s_t}(z_t(k) - z_t(k-1)) \end{cases} \quad (1)$$

Then the position of missile $x_m(k)$, $y_m(k)$ and $z_m(k)$ of the k step is calculated on the basis of $x_1(k)$, $y_1(k)$ and $z_1(k)$, the expressions are as follows:

$$\begin{cases} x_m(k) = x_m(k-1) + \frac{s_m}{c_1}(x_1(k) - x_m(k-1)) \\ y_m(k) = y_m(k-1) + \frac{s_m}{c_1}(y_1(k) - y_m(k-1)) \\ z_m(k) = z_m(k-1) + \frac{s_m}{c_1}(z_1(k) - z_m(k-1)) \end{cases} \quad (2)$$

In expression 2,

$$c_1 = \frac{r(k-1)\sin\beta_{k-1}}{\sin(\alpha_{k-1} + \beta_{k-1})}, \ c_2 = \frac{r(k-1)\sin\alpha_{k-1}}{\sin(\alpha_{k-1} + \beta_{k-1})} \quad (3)$$

In expression 3, $r(k-1) = \sqrt{(x_m(k-1) - x_t(k-1))^2 + (y_m(k-1) - y_t(k-1))^2 + (z_m(k-1) - z_t(k-1))^2}$.

The computation process is as follows:

First of all, Δq is estimated, $\Delta q = \angle T_kM_kB \approx \angle T_kM_{k-1}T_{k-1} = \arccos(\frac{[r(k-1)]^2 + c^2 - s_t^{\ 2}}{2r(k-1)\cdot c})$.

Then the forecast of $x_m(k)$, $y_m(k)$ and $z_m(k)$ can be computed based on Δq according to expressions 1 and 2.

The forecast $\Delta q = \angle T_k M_k B \approx \angle T_k M_{k-1} T_{k-1}$ has error, so it should be corrected, and following expressions can be obtained according to cosine theorem.

$$c_3 = \sqrt{(c_1 - s_m)^2 + (c_2 - s_t)^2 + 2(c_1 - s_m)(c_2 - s_t)\cos(\alpha_{k-1} + \beta_{k-1})}\ ,$$

$$\Delta q = \arccos\left(\frac{(c_1 - s_m)^2 + c_3^2 - (c_2 - s_t)^2}{2(c_1 - s_m)\cdot c_3}\right) - \alpha_{k-1} \tag{4}$$

At last, missile's emended position coordinate $x_m(k)$, $y_m(k)$ and $z_m(k)$ is calculated according to emended Δq in expression 4, expressions 1 and 2.

3.2. Simulation of ship-to-air missile's ideal trajectory

The target's movement factors and flight path can be confirmed by warship according to sensors' detection and tracking before the ship-to-air missile is launched. Assumed that the target keeps the same kind of path from the ship-to-air missile's launch to the end of flight, then ideal trajectory of missile is simulated when the target uses one of the front three kinds of paths, there are shown as figure 3 (a)-(c).

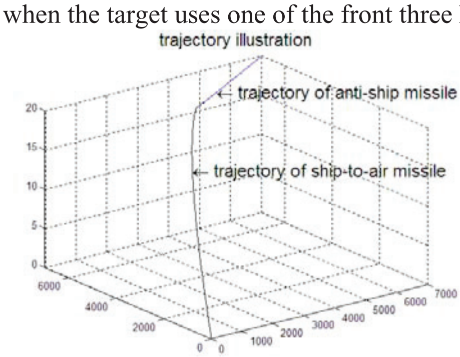

Fig. 3 (a) The illustration of ship-to-air missile's ideal trajectory when target uses low elevation horizontals path

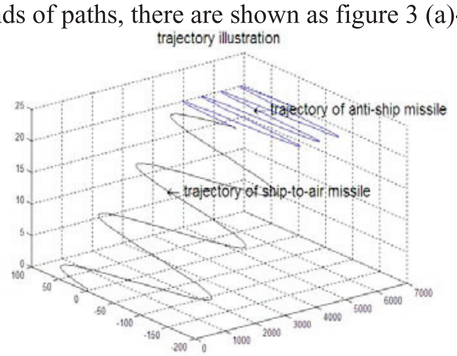

Fig 3 (b) The illustration of ship-to-air missile's ideal trajectory when target uses snaky maneuvering path on the plane

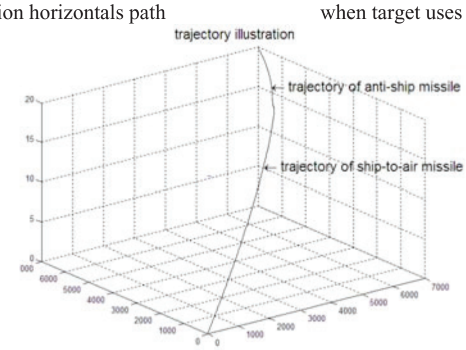

Fig 3 (c) The illustration of ship-to-air missile's ideal trajectory when target uses proportion guidance law on the plane

The simulation predicts ship-to-air missile's ideal trajectory, and it can be seen from simulation result that the trajectory is more smooth when the target uses low elevation horizontal path or proportion guidance path, and the trajectory is more complex when the target uses snaky maneuvering path, so it makes firepower compatibility more difficult to judge if target uses snaky maneuvering path.

At the same time, missile's ideal position coordinate expression of time $\begin{cases} x = f_x(t) \\ y = f_y(t) \\ z = f_z(t) \end{cases}$ can be calculated by trajectory prediction, so the missile's position coordinates during its flight can be predicted before it is launched. This can not only avoid firepower interaction but also exert air-defence efficiency availably, because if other cannon-shots or missiles interact this ship-to-air missile, they don't have to stop during the whole flight course of ship-to-air missile, but just a portion of flight course.

3.3. Analysis of trajectory distribution error

The influence on trajectory from error sources is not considered during ideal trajectory's calculation. Actual trajectory is affected by atmosphere, warship's waggle, detection error of target and control system error of the missile, as a result it forms trajectory distribution entity which makes ideal trajectory as axis, trajectory distribution error as radius. However, the trajectory distribution error will not increase with missile's flight distance, because there is detection equipment on the missile and the missile can modify its trajectory according to detected target position. But if target maneuvers snakily, the missile needs to increase overload to maneuver, which will increase trajectory distribution error, and then the missile makes error less by control system on it continually.

4. Conclusions

Aiming to the problem of ship air-defence firepower compatibility, a trajectory prediction method of ship-to-air missile for dynamic firepower compatibility is advanced. The missile positions during flight can be predicted and expressed to function of time before it is launched. This method can be used to model and simulate missile trajectory in kinematics way, as a result it simplifies computation process compared with kinetics method and reduces computation time, so it can satisfy the need of quick-response during warship's air-defence.

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