**Decoupling Scheme of Tracking Loop of Seeker Based on Disturbance Compensation**

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**Abstract**：To get line-of-sight rate of high-accuracy for guidance, finishing aerial attack and intercept when the missile is controlled by lateral jets which will cause high frequency disturbance to missile attitude, a new decoupling scheme is proposed based on disturbance compensation in this paper. Decoupling-ability, tracking performance and noise rejection ability are analyzed and compared with the two existing method. Simulation and analysis show the effectiveness of the scheme proposed.

**Keywords**：Guidance; Lateral jets; Line-of-sight rate; Decoupling; high-accuracy; compensation

Introduction

Contemporary military strategy has developed from underlining quantity advantage to technical quality advantage. Precision guided weapon is the main way of physical killing, and perform an important role in informatization local wars [1]-[3]. Precision guidance technology is critical for the precision guided weapon, so it is always studied by experts and [researchers](http://dict.cnki.net/dict_result.aspx?searchword=%e5%ad%a6%e8%80%85&tjType=sentence&style=&t=researchers) from many countries.

Seeker is a kind of measuring component in controlling loop of homing guidance [4]. It is required to output information of line-of-sight (LOS for short) rate for guidance. So the precision of its output, LOS rate, affects controlling precision of terminal guidance directly. While a seeker is in the state of tracking, the antenna on it should track the direction of the target. A seeker works on a moving missile. So the disturbance caused by the missile body movement must be separated from the antenna to keep it stable in the inertial space [4]-[5]. The traditional design idea is to use a stabilization loop to attenuate the LOS output caused by body disturbance. We call it traditional multi-loop (TML for short) scheme [4]-[6]. There are also some schemes based on TML scheme, for example, decoupling-loop scheme which changes the position of the loop’s output to improve the decoupling-ability and at the same time have some advantages on design of guidance [7]-[8]. However, it is difficult to decouple disturbance by using the schemes mentioned above. Line-of-sight reconstruction(LOSR for short) scheme, by F.William and Paul Zarchan, can decouple completely in ideal conditions in which the transfer function of the receiver and the gyro are both equal to 1 [9]. In fact, these two conditions can’t be satisfied in the presence of high-frequency disturbance. In modern war, missiles need larger maneuverability to intercept aerial target with high speed and large maneuverability. New types of physical actuators bring high-frequency characteristics to missile movement. The high-frequency characteristics require more effective decoupling method for the seeker. Considering weight and cost, the open-loop gain can’t be too high while the time constant of the servo motor and the gyro fixed on the antenna can’t be too small. These restrictions limit further enhance of decoupling-ability. The existing schemes can only reject disturbance in low frequency segment and very high frequency segment effectively. In the frequency segment which missile moving disturbance can actually reach, decoupling-ability of seekers becomes weaker when missile movement frequency turns high.

In fact, missile disturbance is able to be measured. Gyro fixed on missile for guidance and attitude controlling can measure missile rate information of three channels (pitch, yaw and roll) in real-time. But none of the existing schemes make use of this measurable information effectively. In this paper, a new scheme is brought up to strengthen decoupling-ability of seeker after making full use of the measurable missile rate.

This paper is organized as follows:

Section II gives the problem formulation of seeker’s decoupling and tracking. In section III, a new decoupling scheme, disturbance compensation (DC for short) scheme is proposed and analyzed in detail. After that, simulation and analysis about performances including tracking ability and noise rejection, especially decoupling-ability is done to compare DC scheme and two existing scheme (TML and LOS scheme) in section IV. Finally, we conclude this paper with several conclusions.

1. Problem Formulation

**1.1Basic Control Structure of Seeker**

Seekers are used to tracking a moving target by orienting its antenna so as to always point towards the target. A seeker makes use of a receiver, a angle gyro fixed on its antenna and a servo system (always a motor with controller) to work. In absence of noise, its basic control structure is shown in Fig. 1.



Fig. 1 Basic Control Structure of Seeker

Its working principle is stated by the following:

The tracking-loop of seeker is formed by a receiver and a stabilization-loop which is an inner loop of the tracking-loop. Receiver is a kind of sensor for angular measurement whose output voltage is in proportion to its input error angular. When antenna is not pointing to the target exactly, the receiver outputs a voltage in proportion to the pointing error. To make sure that the antenna pointing is stable in the inertial coordinates, transport motion caused by the body must be separated from the antenna because the seeker works on a moving missile [4]. For this reason, stabilization- loop is established in a way of feedback using servo system and angular rate gyro fixed on the antenna, and the gyro is installed in the feedback channel. When missile movement transfers to the antenna, feedback signal tapped from the gyro (voltage in proportion to turning rate of antenna pointing in relative to inertial space) drives the servomechanism to rotate in the opposite direction, annulling the effect of body rate disturbances in the synthesized antenna pointing rate.

The definition of variables target LOS, antenna pointing, missile body axis, and inertial axis is shown in Fig. 2.



Fig. 2 Definition of Variables

Where T represents target, A represents antenna and x1 represents missile body axis. The variables, , ,  and  are defined to be LOS angle, missile body attitude angle, antenna pointing angle, gimbal angle (angle between antenna and missile body axis), and antenna pointing error angle separately.

**1.2Decoupling Performance Restrictions**

Decoupling-ability is always limited by time constants of gyro and motor. This can be explained by the following analysis:

Ignore controller of the motor for convenience, and isolate stabilization-loop of seeker from the whole seeker’s tracking system, we get Fig. 3.

Where  is transfer function of motor and  is transfer function of angle rate gyro fixed on antenna. , and  is differential of ,  and  respectively.



Fig. 3 Angle Stabilization-loop

From Fig. 3, we can see that the output from  to  can reflect seeker’s decoupling-ability. The smaller the modulus of  is, the better decoupling-ability the system has.  and  are defined as follows:





Where  is motor gain,  is time constant of motor. ,  and  is gain, time constant and damping ratio of gyro on antenna.

So, we have



In order to get better decoupling, we always design . Approximately, we have



According to (4), decoupling performance bode diagram is shown in Fig. 4.

From Fig. 4, it can be seen that stabilization-loop’s rejection of missile disturbance is strong in low frequency and becomes weaker in medium and high frequency. To obtain better decoupling-ability, gyro time constant  and motor time constant  should be reduced, and gyro gain  and motor gain  should be increased. But the degree that these constants can reduce or increase is limited by cost, weight, and physical achievability. Therefore, decoupling bandwidth can’t be designed too wide.

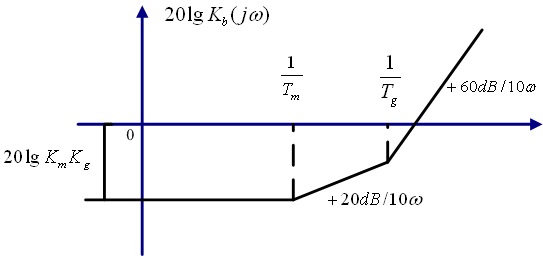


Fig. 4 [Decoupling](javascript:showjdsw('jd_t','j_')) Performance Bode Diagram

2. Decoupling Scheme of Seeker Based on Disturbance Compensation

**2.1DC Scheme**

To overcome that decoupling-ability turns weak when frequency turns to medium and high frequency segment, a DC scheme is presented in this paper, in which the disturbance is measured by gyro on missile body and compensated to stabilization-loop through certain link. Block diagram of DC scheme is shown in Fig. 5.



Fig. 5 Disturbance Compensation Decoupling Scheme

Where  is estimation of LOS angle rate,  is transfer function of filter,  is transfer function of receiver,  is transfer function of power amplifier,  is controller of motor,  is transfer function of gyro in missile body and  is rectification set designed according to system parameters and requirement.  and  make up of the disturbance compensation channel.

**2.2Decoupling Principle of DC Scheme**

Theoretically, DC scheme can decouple absolutely without stabilization-loop. But full-compensation can’t be achieved in actual situation. Therefore，the stabilization-loop is still kept.

By Mason formula, assumption of full-compensation is



That is



Where





Where  and are time constant of motor controller ,  is time constant of gyro in missile body, and  is damping ratio of gyro in missile body.

Because the numerator of  is three orders higher than the denominator,  is only proper theoretically, but can’t be achieved. Therefore, only partial-compensation is considered. In fact, bandwidth of gyro  fixed on missile body is wider than that fixed on antenna. Time constant of  can be made small. In this case, dynamic process of this gyro can be ignored in bandwidth of stabilization-loop to make partial-compensation. That is . Then  can be easily designed to be



Where  is a small time constant for realization.

The smaller the time constants  and  are, the better decoupling-ability DC scheme has. Therefore, when designing ， time constants  and  should be chosen as small as possible.

3. Performance Analysis, Simulation and Comparison

**3.1TML and LOSR Scheme**

Control structure of TML [8] scheme is shown in Fig. 6.



Fig. 6 Traditional Multi-loop Scheme

Where  and  are stabilization-loop and tracking-loop respectively.  is used to separate the missile body rate output in order to stable the antenna in inertial space, and  is designed to finish the tracking function. TML scheme is based on the control structure in Fig. 1, strengthening its decoupling-ability by designing proper controller and rectification device.

LOSR scheme is proposed by F.William Nesline and Paul Zarchan first [9], shown in Fig. 7.

Where  is voltage corresponding to error angle output from receiver,  is the reconstructed LOS angle,  is differential and filter link and  is output of LOSR (LOS rate).



Fig. 7 Line-of-Sight Reconstruction Scheme

The design idea of LOSR is: Gyro fixed on antenna measures antenna’s angle rate with respect to inertial space. The output of the gyro is integrated to give antenna pointing angle . Adding it to error angle , which is output of receiver, LOS angle  is obtained, shown in Fig. 2 and Fig. 7. Through a differential and filter link , the estimation of LOS rate,  is obtained.

**3.2Decoupling-ability**

Define decoupling coefficient as ratio of output and disturbance input, signing it by Sx. The smaller modulus of Sx is, the better decoupling a scheme has.

According to Fig. 5, decoupling coefficient of DC scheme can be given by



Here  is decoupling coefficient of DC scheme.

Similarly, according to Fig. 6 and Fig. 7, decoupling coefficient of TML and LOSR scheme can be given by



and



Where



and



Here  and  are decoupling coefficients of TML and LOSR scheme respectively.

From the coefficients of the three schemes, we can analysis decoupling-ability of them. The modulus of  is smaller in low and very high frequency than middle and high frequency, because the partial-compensation is very near to full-compensation in low frequency according to its design, and when frequency is very high, the modulus of  will [decrease](http://www.iciba.com/decrease/) for denominator’s increasing, but these two effects are neither significant in middle and high frequency. For TML scheme, it decouples all by feedback. Modulus of  is small enough in low frequency for big stabilization-loop gain. When frequency turns higher and higher, its decoupling-ability becomes weaker and weaker, until the frequency is high enough to make the effect of denominator’s increasing significant as DC scheme. LOSR scheme has a similar trend. In low frequency,  and  are both nearly equal to 1. Therefore, its decoupling performance is very good [9]. And in very high frequency, its decoupling-ability turns good, but worse than the other two schemes because of the differential link.

Comparison of decoupling-ability is given in Fig. 8. Parameters are chosen as Table. I. It can be seen from Fig. 8 that analysis about decoupling performance is right.



Fig. 8 Decoupling Coefficient Bode Diagram of Three Scheme

TABLE

Parameters of Three Schemes

|  |  |  |  |
| --- | --- | --- | --- |
| Serial number | Symbols | Physical meaning | values |
| 1 |  | Motor gain | 200 |
| 2 |  | Motor time constant | 0.5s |
| 3 |  | Receiver gain | 1 |
| 4 |  | Receiver time constant | 0.05s |
| 5 |  | Gain of gyro on antenna | 1 |
| 6 |  | Time constant of gyro on antenna | 0.02s |
| 7 |  | Damping ratio of gyro on antenna | 0.7 |
| 8 |  | Power amplifier | 6 |
| 9 |  | Filter time constant | 0.1s |
| 10 |  | Small time constant of rectification device | 0.01s |
| 11 |  | Gain of gyro on missile body | 1 |
| 12 |  | Time constant of gyro on missile body | 0.002s |
| 13 |  | Damping ratio of gyro on missile body | 0.7 |
| 14 |  | Time constant 1 of motor controller | 0.357s |
| 15 |  | Time constant 2 of motor controller | 5s |

Missile body disturbance frequency is 0-10Hz, corresponding to 0-62.8rad/s. The worst frequency points of three schemes, which make the decoupling coefficients the largest in their bode diagrams, are all in this frequency segment. Therefore, decoupling coefficients at the worst frequency points can reflect the decoupling-ability of the three schemes. The worst frequency point, the corresponding decoupling coefficient amplitude, and disturbance output percent of three schemes are shown in Table. II.

It can be seen form Table. II that, DC scheme has the best decoupling-ability, with disturbance output 1.46%, while TML scheme has the worst decoupling-ability, with disturbance output 12.74% at their worst frequency points.

TABLE II

Decoupling Performance of Three Schemes

|  |  |  |  |
| --- | --- | --- | --- |
| Scheme | The worst frequency point | Decoupling coefficient amplitude | Disturbance output percent |
| TML | 7.38rad/s | -17.9dB | 12.74% |
| LOSR | 30.6rad/s | -21.9dB | 8.04% |
| DC | 11.6rad/s | -36.7rad/s | 1.46% |

According to Fig. 8 and Table. II, conclusions can be drown as follows:

First, medium and high frequency segment is the most critical for decoupling-ability, because decoupling-ability of three schemes all turns worse when missile body disturbance frequency increases to medium and high frequency segment but better when in low and very high frequency segment.

Second, DC scheme has the best decoupling-ability of the three, because its decoupling coefficient is the smallest at their own worst frequency points.

**3.3Tracking Performance**

According to Fig. 5, Fig.6 and Fig.7, closed-loop transfer functions of DC, TML and LOSR schemes are respectively





and



The tracking loop of TML scheme and DC scheme are the same. Therefore, they have similar tracking performances. Bode diagram of closed-loop transfer functions of three schemes is shown in Fig. 9.

It can be seen that bandwidth of TML and DC scheme is 4.83rad/s and that of LOSR scheme is 6.95rad/s. Bandwidth of LOSR is wider, so tracking performance of this scheme is better.



Fig. 9 [Closed-loop Transfer Function](http://dict.cnki.net/dict_result.aspx?searchword=%e9%97%ad%e7%8e%af%e4%bc%a0%e9%80%92%e5%87%bd%e6%95%b0&tjType=sentence&style=&t=closed-loop+transfer+function) Bode Diagram of Three Scheme

**3.4Noise Rejection**

There are many kinds of noise in seekers. For convenience, we make all noise effect equivalent to that inputs before the receiver. The block diagrams of three schemes are separately shown in Fig. 5, 6 and 7. TML scheme and DC scheme have the same transfer relationship of noise input and LOS rate output, while LOSR scheme amplify the noise badly because of the differential link before output. In the presence of the same noise, the outputs of noise of three schemes are shown in Fig. 10.



Fig. 10 Noise Output of Three Schemes

Where the X-axis represents the number of sample time. When setting the same noise input, the noise output of LOSR scheme is obviously more than that of TML scheme and DC scheme.

4. Conclusion

In this paper, a new decoupling scheme based on disturbance compensation is investigated for seeker tracking loop, which is compared with TML and LOSR scheme. Some conclusion remarks are obtained as follows: Advantage of DC scheme is that, it makes full use of gyro fix on missile body to measure turning rate information of missile body, reaching a good decoupling result. TML and LOSR schemes can’t generate effect information for homing guidance when considering high frequency characteristic caused by complex control of direct lateral force and pneumatic force. Though tracking performance of LOSR scheme is better than DC scheme, noise rejection ability of it is weaker. Considering decoupling-ability, tracking performance and noise rejection ability, DC scheme are able to generate more precision LOS rate information, finishing precision homing guidance under the circumstances of direct force.

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