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Improvement of Quality of Missile Guidance Through Compensation for Errors of Nose Cone

Nguyen Minh Hong
Le Quy Don technical university, Ha Noi, Social Republic of Viet Nam
nguyenhaihong2007@bk.ru

Abstract. The Nose cone is an integral part of the missile, with the role of protecting the self-guided head from the effects of the environment during the flight. However, the Nose cone also causes the error component of the angle due to the electromagnetic refraction effect when passing through the Nose cone, causing the missile guidance error. This article will analyze the relationship among the angular components during the proximity to the target of the missile, thereby using filters along with the dither signal to determine the angular error component caused by the Nose cone to eliminate the effect of the said error component
This article proposes a simple compensation and rejection scheme based on the dither signal. With the proposed compensation scheme, the calculated volume is significantly reduced when compared to the method of compensation by the Kalman filter. The Nose cone error compensation ability of the compensation scheme proposed in this article will be verified through simulations on the MATLAB software. The results of the article will show that the Nose cone coefficient can be quickly estimated using a dither signal, bandpass filter and notch filter, so that we could get information about the Nose cone coefficient. With the practicality of the article results, it can be applied to radio self-guided head of the self-guided missile system to improve the quality of proximity to the target, reduce slippage at the time of meeting.

1. Problem

All self-guided missiles using radar signals and operating in the atmosphere must use a Nose cone to protect the self-guided head from the effects of environmental factors. The Nose cone should ensure that the reflective signals from the target to the Nose cone not to be distorted or declined too much. However, the reflective signals to the Nose cone have to pass through different environments, which results in the refraction of signals before reaching the missile self-guided head, distorting information about the target position and causing the incorrect missile control. In other words, the signal refraction phenomenon through the Nose cone causes the instability in the missile guidance system. The problem of missile stability will become more urgent as the flight altitude of the missile increases [1], [2], [3].
An approach to reduce the effect of refraction phenomenon due to the Nose cone is to increase the time constant of the guidance system. The advantage of of this approach is being easy to implement but increasing the slippage. Another, more common, approach to solving the refraction problem due to the Nose cone is to use the checklist to perform the compensation that is stored in the computer on the missile compartment. With this method, a sample Nose cone will be surveyed and measured in an anechoic chamber (non-reflective), and then the results of the measurement will be stored in the computer on the compartment for use in compensation for effects of the refraction phenomenon on the

Nose cone. It is clear that the accuracy and effectiveness of this method depend on the accuracy of the measurements as well as the accuracy of the sample Nose cone model. If the Nose cone used in practice is different from the sample Nose cone or the electrical properties of the Nose cone are not the same as the ones when carried out in the measurement chamber, it may result in a significant reduction in the quality of the guidance system [4]. In general, when considering the effect of the Nose cone on the quality of the guidance system, the conditions of consideration are usually limited to the flight height for self-guided missiles controlled aerodynamically.

Based on the above analysis, this article proposes a method to reduce the effects of the refraction phenomenon due to the Nose cone of the self-guided head to improve the guidance quality of missile at the high altitude.

2. Research method

2.1. Theoretical basis

For different purposes, the authors use different assumptions for the guidance problem, leading to different structural diagrams. However, one of the diagrams widely used in researches on guidance law of Zarchan [5] is shown below:

Figure 1.Diagram of a self-guided ring structure taking into account the effects of the Nose cone error

In which:

- Dynamic geometry is taken based on the assumption that the angels of the sightline λ (which is the result of the relative distance division on the Y axis for the space from the missile to the target,R_{TM}) and the target flight angle γ_T are small enough to linear the distance, velocity, and relative torque components between the missile - target on the Y axis.

- The self-guided head model is constructed according to the LOS Restructuring method [6], where: θ is the nod angle of the missile; D is the angle of sightline of the self-guided head; θ_H is the angle of the propeller shaft (the angle between the sightline of the self-guided head and vertical shaft of the missile); ε_s is the angle between the actual position of the missile-target sightline and the self-guided head sightline (actual proximity error); r is the angle error caused by the Nose cone phenomenon; ε_m is the measured proximity error value; λ is the LOS angle; λ_m is the measured LOS angle; $R_s = \dfrac{dr}{d\theta_H}$ is the Nose cone error coefficient, however in a variable range of θ_H, R_s is considered a constant coefficient [6], [7]; T_s is the time constant of the proximity ring of the self-guided head.
- The low-pass filter with a time constant t_F is responsible for processing the sightline angle speed signal before it is sent to the guidance computer.
- The guidance computer on the compartment is responsible for calculating the guidance command n_M according to the proportional approach guidance law [7], [8].
- The limit stage similates the allowable maneuverability of the missile with the allowable normal acceleration command value as n_{lim}.
- The kinematics of the flight control system is modeled by three magnitude-1 inertia stages with a time constant t_{FCS} [5] having the input as the limited guidance command and the output as the missile normal acceleration n_L.
- The nod angle speed is reflected back to the self-guided ring through the transfer function of the nod angle speed with the time constant of the rotary speed T_α [5], [8]

Below is the result of the slippage survey of the guidance system by the flight time of the missile based on the above structure diagram.
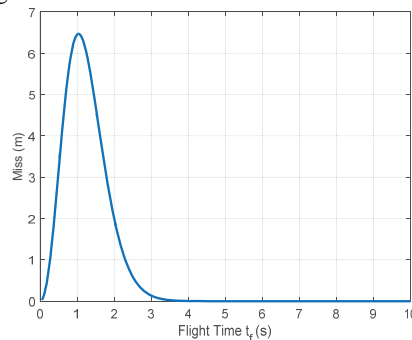

Figure 2. The slippage of the guidance system when not affected by the Nose cone error

2.2. Filters Used for Compensating the Nose Cone Error

a) Bandpass Filter

Bandpass filters are mainly used in digital signal processing applications and are used to extract/filter sinusoidal signals with the known out-of-interference frequency. These types of filters have a general transfer function in the form of [9]:

$$H(s) = \frac{Ks^n}{\left(1 + \frac{s}{\omega_0}\right)^{2n}}, n = 1,2,3, \dots \qquad (1)$$

Where $2n$ determines the maginitude and the K coeffient is chosen to ensure the amplification coefficient of the filter to be equal to 1 at the private frequency ω_0 of the filter. The Figure 3 describes the amplitude variation of Bandpass filters by the magnitude of the filter.
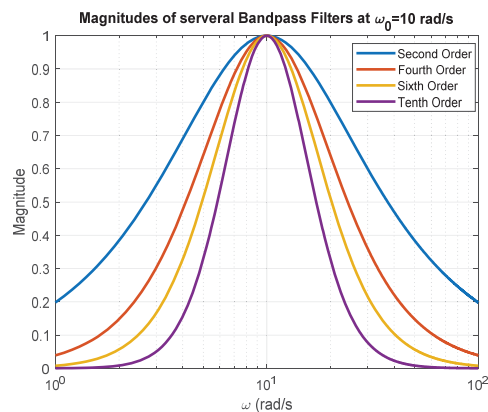
Figure 3.Amplitude of several Bandpass filters with different magnitudes

b) Notch Filter

The notch fitter has the properties opposite to the ones of the bandpass filter; in particular, it allows any signal passing through, except for the signal with the same frequency as the center frequency of the filter. The notch filter has a transfer function as follows [10]:

$$H(s) = \frac{s^2 + 2gmin * damp * freq * s + freq^2}{s^2 + 2 * damp * freq * s + freq^2} \qquad (2)$$

in which the parameters of $gmin$, $damp$, and $freq$ are the parameters of the notch filter and shown in Figure 4.
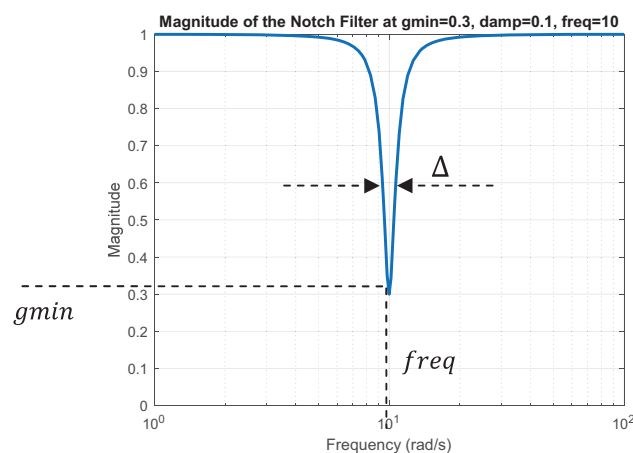
Figure 4. Parameters used for adjustment of the notch filter
$gmin$ is the depth of the filter, $freq$ is the center frequency of the filter, and $damp$ decides the width Δ of the filter (the larger the $damp$ is, the larger Δ is).

2.3. Proposed Scheme to Compensate for the Nose Cone Error Using Dither Signal

So far, there have been numerous articles published on studies related to the successful application of the Kalman filter to estimate the Nose cone coefficient [1], [11]. However, this article proposes a simpler approach, with less computational volume to estimate the Nose cone coefficient using a dither signal, a bandpass filter, and a notch filter.

The idea of using dither signals for estimation purposes is not new because it has been used in studies by Stallard [12] and Gratt [13]. Stallard applied dither signals to the self-driving design process, while Gratt applied the dither to the Nose cone estimation problem.

In the proposed scheme, a dither signal with the fixed amplitude and frequency is added to the PN normal acceleration command. The amplitude of the dither signal is chosen reasonably, and the frequency is high enough compared to the bandwidth of the system to ensure that it does not increase the system slippage. When adding a dither signal in the sinusoidal form with the period ω_0 and the amplitude A to the normal acceleration command at the output of the guidance computer, if the missile guidance system is designed to work in the linear range, ie the normal acceleration command is not limited, the measurements of the measured missile nod angle θ, the angle of the propeller shaft θ_H and the error angle of the self-guided head ε_m will have degraded signal components when passing through bandpass filter with the center frequency exactly equal to the frequency of the dither signal. At that time, if we divide the measure error angle signal of the self-guided head after passing through the bandpass filter by the angle signal of the propeller shaft filtered by the bandpass filter, we will obtain an estimate of the Nose cone coefficient. The scheme of compensation for the Nose cone error is shown in Figure 5 below.

Figure 5. Diagram of a self-guided ring structure with compensation for the Nose cone error
Where:
- $A \sin \omega_0 t$: the dither signal with the amplitude A, and the frequency ω_0.
- BPF: the bandpass filter with the center frequency equal to the frequency of the dither signal.

- NF: the notch filter with the center frequency equal to the frequency of the dither signal.
- $Divide$: the stage for implementation of the division
- $Multiply$: the stage for implementation of the multiplication.
- Add: the stage for implementation of the addition.
- T_R: the time constant of the low pass filter that removes the peak of the mutation in the Nose cone coefficient estimate signal caused by the division in the stage of $Divide$.

In the case where the value of the angle of the propeller shaft is 0, the automatically estimated Nose cone coefficient shall be set by the computer as 0 to avoid the case of estimation of the Nose cone assuming infinity as the result of the division by 0. Althoud the Nose cone error coefficient is variable, however, based on the experience, we can assume that the Nose cone coefficient varies over a given range. This article assumes that the Nose cone coefficient varies in the range from -0.06 to +0.06.

Let λ^*, θ^*, và θ_H^* be the inner angles in the case the self-guided ring has the dither signal and λ, θ, và θ_H be the inner angles in the case the self-guided ring does not have the dither signal. Then, from the figure 5, we have:

- Sightline angle:
$$\lambda^* = \lambda \tag{3}$$
- Direction angle:
$$\theta^* = \theta \tag{4}$$
- Propeller shaft angle:
$$\theta_H^* = \theta_H + \theta_{H_d} \tag{5}$$

In which θ_d and θ_{H_d} are components that contain information about the dither signal.

- Measured error of the self-guided head:
$$\varepsilon_m = \lambda^* - \theta^* - \theta_H^* + R_s \theta_H^* \tag{6}$$

From (3), (4), (5), we can present (6) as follows:
$$\varepsilon_m = \lambda - \theta - \left(\theta_H + \theta_{H_d}\right) + R_s\left(\theta_H + \theta_{H_d}\right) \tag{7}$$

Because the property of the bandpass filter is only allowing passing through the signal with the same frequency to the center frequency of the filter. Therefore, when allowing passing through the ε_m and θ_H^* signals, only the component that carries information about the dither signal can pass through the filter. Let ε_m' and θ_H' are the measured error of the self-guided ring and the propeller shaft angle respectively after passing through the bandpass filter. Then we have:
$$\varepsilon_m' = \theta_{H_d}(R_s - 1) \tag{8}$$
$$\theta_H' = \theta_{H_d} \tag{9}$$

After putting the two signals above through the Divide stage, and adding the result with 1, we can estimate the Nose cone coefficient $\hat{R}_s$:
$$\hat{R}_s = \frac{\varepsilon_m'}{\theta_H'} + 1 \tag{10}$$

After putting the estimated signal of the Nose cone coefficient $\hat{R}_s$ through the low pass filter to remove the mutations and multiplying by the measured propeller shaft angle signal, we obtain the estimated signal of the error angle due to the Nose cone ; and this angle is brought back to the self-guided ring to remove the error due to the Nose cone .

3. Result

The results of the article will show that the Nose cone coefficient (the important parameter associated with the false angle caused by the Nose cone) can be quickly estimated using a dither signal, a bandpass filter and a notch filter, so that we can get information about the Nose cone coefficient. It then determines the error angle of the signal caused by the refraction phenomenon in the Nose cone, thus making the compensation for this error angle at the guidance signal.

The article will survey two specific examples to illustrate the compensation for the Nose cone error when the Nose cone coefficient is constant by the proposed compensation scheme. Simulations are performed on the MATLAB environment.

Below is a table of parameters used to survey the possibility of compensating the Nose cone error of the proposed scheme.

Table 1. Value of parameters used for survey

Sampling speed: 0.1s	Time constant of the self-guided head: 0.1s
Guidance constant N': 3	Time constant of the flight control system: 0.1s
Missile velocity: 1200 m/s	Time constant T_R of the low pass filter: 0.5s
Proximity velocity: 1800 m/s	Time constant T_R of the low pass filter: 0.1s
Time constant T_α: 5s	Target normal acceleration: 3g (g = 9.8 m/s)
Maximum flight time: $t_{f_{max}} = 10$s	Initial distance between missile - target: 10000 m
Allowable maximum normal acceleration of the missile: 20g (g = 9.8 m/s)	

The article will survey the slippage of the missile and the accuracy of the Nose cone error coefficient value estimated by the proposed compensation scheme in both cases: the Nose cone error coefficient is negative and the Nose cone error coefficient is positive.

Case 1: The Nose cone error coefficient is negative

In this case, we assume that the value of the Nose cone error value is -0.01, the frequency of the dither signal is $\omega_0 = 50$ rad/s, the applitude of the dither signal is: 30g.
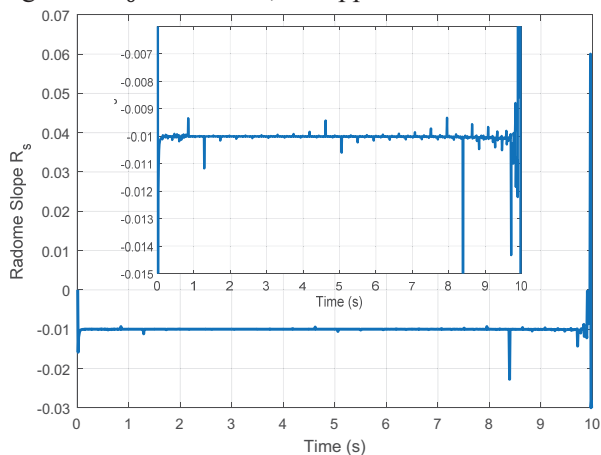

Figure 6. Estimated Nose cone coefficient before passing through the low pass filter with the time constant of T_R
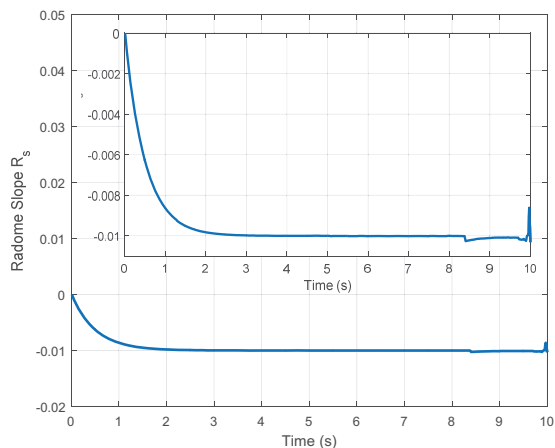
Figure 7. Estimated Nose cone coefficient after passing through the low pass filter with the time constant of T_R
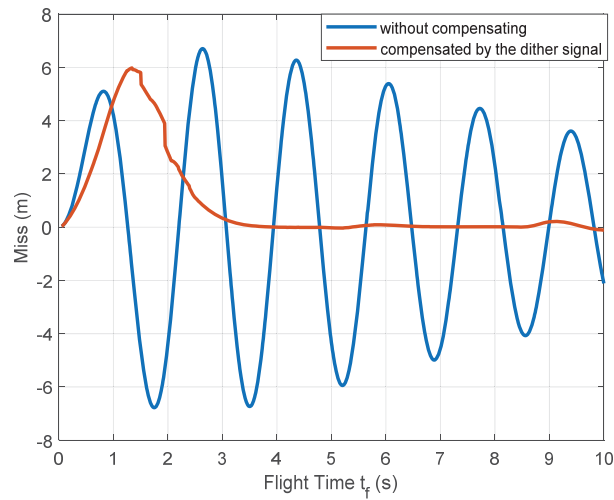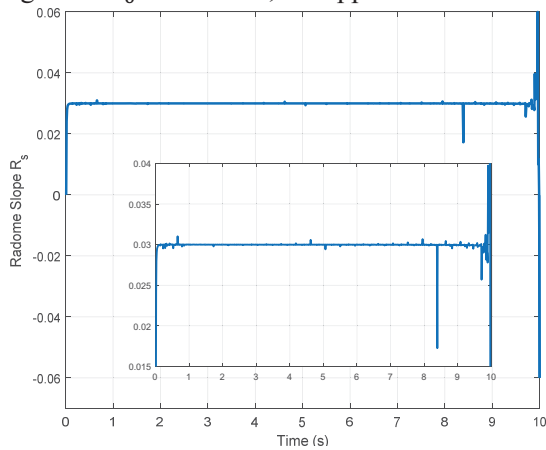
Figure 8. The slippage of the missile by the flight time t_f when compensated for the Nose cone error by the dither signal and not compensated

Case 2: The Nose cone error coefficient is positive

In this case, we assume that the value of the Nose cone error value is 0.03, the frequency of the dither signal is $\omega_0 = 50$ rad/s, the applitude of the dither signal is: 30g.

Figure 9. Estimated Nose cone coefficient before passing through the low pass filter with the time constant of T_R
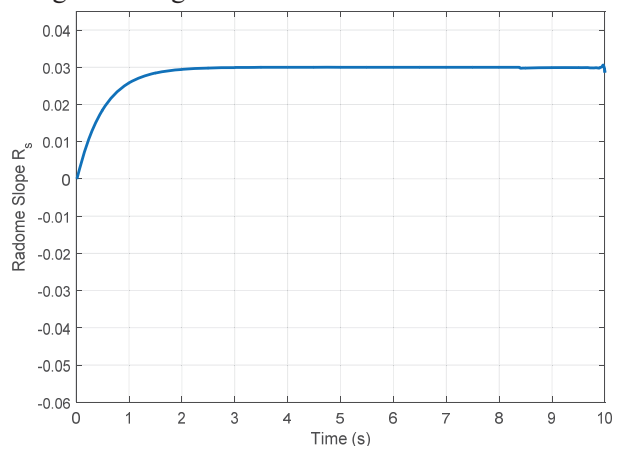

Figure 10. Estimated Nose cone coefficient after passing through the low pass filter with the time constant of T_R
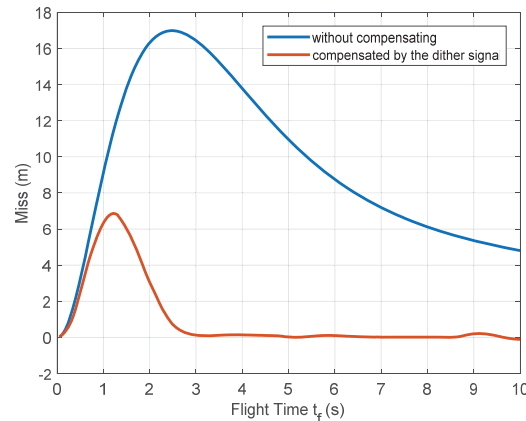
Figure 11. The slippage of the missile by the flight time t_f when compensated for the Nose cone error by the dither signal and not compensated

4. Comment:

From Figure 6 and Figure 9, we can see that the estimated Nose cone coefficient value obtained after the division coincides with the actual value of the Nose cone coefficient. However, the estimated value is obtained from the division process, so it cannot avoid the mutations. To eliminate the mutations, the Nose cone coefficient estimate is applied to the low pass filter with a time constant T_R. The Figure 7 and the Figure 10 show that, since the 2nd second of flight process, the Nose cone error coefficient received after passing through the filter has almost exactly coincided with the actual value of the Nose cone coefficient.

After making the compensation for the Nose cone error according to the proposed scheme, the slippage of the guidance system has improved significantly compared to the non-compensated system (Figures 8 and 11). In comparison with Figure 3 (The graph shows slippage when assuming the system is not affected by the Nose cone error) with the red line on Figure 8 and Figure 11 showing the slippage of the guidance system when compensated according to the proposed scheme, such three lines are almost identical. This shows the efficiency in compensating for Nose cone error of the dither signal.

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