Static Decoy for Countering Anti-Radiation Missiles Against Ship-Borne Radars

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Abstract—This paper proposes an efficient decoy system structure designed to protect air-defense radar systems. In the past, decoy systems required an extensive surface area for deployment, and worked by diverting anti-radiation missiles to their location by creating greater energy density. In this way, in old models the decoy sacrificed itself to save the radar site. The evolution of decoy systems made it possible for them to protect themselves through the use of multiple decoys. However, an extensive area is still required to deploy these systems, leading to many restrictions on applications that require deployment within a smaller surface area (naval applications on ships are one example of this). The model proposed in this article diverts anti-radiation missiles into the safe range of an air-defense site, by controlling phase and amplitude of the received signal and using angular error on a mono-pulse missile tracker created by glint phenomena. This method allows for reduction of the land surface area required for decoy system deployment. The effectiveness of the proposed method is approved and evaluated using theoretical relations and simulation results.

Keywords—Radar; Decoy; Anti-radiate missile; Ship; Glint

I. INTRODUCTION

The best way to counter the attack of air targets is through the use of radar systems, which are the foundation of air defense. On the other hand, the attacking targets commonly use techniques such as reduction of radar cross-sections, jamming, and deceptive techniques to evade the radar. Anti-radiation missiles are the most lethal offensive armament against a radar system, and pose a serious threat to defense systems. Therefore, an effective method to divert anti-radiation missiles from radar sites is necessary to protect equipment related to the radar systems.

In related literature, various methods (e.g., the use of bait decoy, self-guarding decoy systems) have been proposed for countering anti-radiation missiles.
\( r_0 \): Distance between anti-radiation missile and radar

\( r_1 \): Distance between anti-radiation missile and decoy

Received signals in radar have phases proportional to \( 2r_0 \) and \( r_0 + r_1 \)

Received signals in decoy have phases proportional to \( 2r_1 \) and \( r_0 + r_1 \)

Assuming that the emitted intermediate frequency (IF) signal from radar is \( \cos(\omega t + \varphi_0) \) and from decoy is \( \beta \cos(\omega t) \), and \( \varphi_0 \) is the phase difference between them.

IF signals received by radar and decoy are \( S_0 \) and \( S_1 \)

\[
S_0 = E_0 \beta \cos\left(\omega t - \frac{2\pi}{\lambda} (r_0 + r_1)\right) + E_0 \cos\left(\omega t - \frac{2\pi}{\lambda} r_0 + \varphi_0\right)
= E_0 (\beta \cos(\omega t + \varphi_1) + \cos(\omega t + \varphi_2))
\]

\[
S_1 = E_1 \cos\left(\omega t - \frac{2\pi}{\lambda} (r_0 + r_1) + \varphi_0\right) + E_1 \beta \cos\left(\omega t - \frac{2\pi}{\lambda} r_1\right)
= E_1 (\cos(\omega t + \varphi_1') + \beta \cos(\omega t + \varphi_2'))
\]  

Phase difference of \( \Delta \varphi = \varphi_1 - \varphi_2 \) measured in the radar or decoy receiver is equal to the phase difference in anti-radiation missile PRS\(^1\).

The output signals of radar and decoy, \( S_0 \) and \( S_1 \) are mixed with a controllable local oscillator signal, namely \( S \), defined as:

\[
S = E \cos(\omega t + \varphi)
\]  

\(^1\) PRS: passive radar seeker.

In the next step, these signals pass through a low-pass filter; the results are shown in Fig. 3 and by changing phase signal of local oscillator \( \varphi \), we find maximum value of output signal from low-pass filter, then we have \( \varphi_{1\text{max}} \) from maximum of \( S_0 \times S \) and \( \varphi_{2\text{max}} \) from maximum of \( S_1 \times S \) then value of phase difference is \( \Delta \varphi = \varphi_{1\text{max}} - \varphi_{2\text{max}} - \varphi_0 \) this shown in Fig. 4.
difference signal \( d/S \) is real [5]. In the case of unresolved targets, however, \( s \) and \( d \) may have any relative phase, and their ratio is therefore complex. To demonstrate this fundamental point in a simple way [6, 7], consider two unresolved targets at different angles within the beam. Considering each of two angular coordinates, this introduces a glint-related error in the monopulse system [11].

In the phase diagram shown in Figure 5, \( s_a \) and \( d_a \) are the monopulse sum and difference signals from the first target, and \( s_b \) and \( d_b \) the corresponding signals from the other. Although both targets are in the same range resolution cell, in general their ranges are not exactly the same. This leads to a degree of phase difference between \( s_a \) and \( s_b \). Even if the ranges are equal, there may be a phase difference because of different backscatter phase characteristics of the two targets. The resultant \( s \) is the sum of two signals. Suppose, for illustration, that the two targets are on opposite sides of the beam axis, with the first target on the side that causes \( d_a \) to be in phase with \( s_a \); in this scenario, \( d_b \) is in opposite phase of \( s_b \). The total difference signal \( d \) is the resultant difference of \( d_a \) and \( d_b \).

![Fig 5. Phase diagram of two target](image)

It is clear from Fig 5 that, in general, \( d \) has a quadrature component with respect to \( s \), shown by the dashed line, as well as an in-phase component. In other words, the ratio \( d/s \) is complex. It is also easy to see that if \( s_a \) and \( s_b \) are 180° out of phase and nearly equal in magnitude, the ratio \( d/s \) can become very large.

To express the result mathematically, let \( \theta_a \) and \( \theta_b \) be the angular displacements of the two targets from the axis in the selected coordinate. Relation between sum and difference components for each target is:

\[
\frac{d_a}{s_a} = k_m \frac{s_a}{s_a} \tag{4}
\]

\[
\frac{d_b}{s_b} = k_m \frac{s_b}{s_b} \tag{5}
\]

The resultant indicated angle is

\[
\theta_i = \frac{1}{k_m} \frac{d}{s} \tag{6}
\]

\[
\theta_i = 1 \left( \frac{d_a}{s_a} + \frac{d_b}{s_b} \right) \frac{\theta_a s_a + \theta_b s_b}{s_a + s_b} \tag{7}
\]

Eq. (7) states that the indicated angle \( \theta_i \) is a weighted average of the actual angles of the targets, with weightings proportional to their respective sum-signal contributions. However, the weighting is complex, since \( s_a \) and \( s_b \) in general have different phases, and the result is not clear without further analysis [7, 8].

This equation can also be written in another form that expresses the indicated angle to the true angle of the first target, \( \theta_a \), plus an error term; this form is convenient for determining the error in measuring the angle of a particular target:

\[
\theta_i = \theta_a + \Delta \theta \times \text{Re} \left\{ \frac{pe^{j\phi}}{1 + pe^{j\phi}} \right\} \tag{8}
\]

The quantity \( \theta_i \) on the left-hand side of (8) has been named the complex indicated angle, or, simply, the complex angle [9]. The indicated angle equals the geometric angle, regardless of the amplitudes and phases of the two targets. However, in general the indicated angle is a complex quantity. The monopulse processor is normally designed to extract only the real part of the indicated angle. Real part of the indicated angle can be written as:

\[
\theta_i^{\text{real}} = \theta_a + \Delta \theta \times \text{Re} \left\{ \frac{pe^{j\phi}}{1 + pe^{j\phi}} \right\} \tag{9}
\]

Given that \( e^{\pm j\phi} = \cos \phi \pm j \sin \phi \), we have:

\[
\text{Re} \left\{ \frac{pe^{j\phi}}{1 + pe^{j\phi}} \right\} = \text{Re} \left\{ \frac{pe^{j\phi}}{1 + pe^{j\phi}} \right\} \frac{1 + e^{-j\phi}}{1 + pe^{-j\phi}} \tag{10}
\]

\[
\frac{pe^{j\phi} + p^2 \cos^2 \phi + p^2 \sin^2 \phi}{1 + 2p \cos \phi + p^2} = \frac{p \cos \phi + p^2}{1 + 2p \cos \phi + p^2} \tag{11}
\]

By substituting \( \Delta \theta = \theta_a - \theta_b \) in (9), we have:

\[
\frac{\theta_i^{\text{real}} - \theta_a}{\theta_a - \theta_b} = \frac{p \cos \phi + p^2}{1 + 2p \cos \phi + p^2} \tag{12}
\]

It can be seen from Fig. 6 that \( \theta_a - \theta_b \) and \( \theta_i - \theta_a \) are respectively equal to \( \theta_d \) and \( \Delta \theta_c \). So:
\[
\frac{\Delta \theta_e}{\theta_D} = \frac{pcos\phi + p^2}{1 + 2pcos\phi + p^2}
\] (13)

Where \(\Delta \theta_e\) is the amount of angular error, and \(\theta_D\) is view angle in PRS between radar and decoy line of sights. \(p\) and \(\phi\) are the amplitude ratio and phase difference between two targets, respectively.

**Fig 6. Two-target model [10]**

### IV. Simulation Results

Equation (13) can be used to calculate the amount of angular error created in an anti-radiation missile monopulse tracker system during simulation. Suppose that \(p = 0.6, \ 0.7, \ 0.8, \text{ and } \theta_D = 6^\circ\). The resulted angular errors are shown in Figure 7. Now suppose that the amplitude ratio is equal to 0.8. Curves of \(\Delta \theta_e\) for values of 2, 4, and 6 degree of \(\theta_D\) are represented in Fig 8.

**Fig 7. Angular Errors with different amplitude ratios**

**Fig 8. Error angular with different \(\theta_D\)**

When the angular error has a negative value in the monopulse seeker of the anti-radiation missile, the missile is led to a zone beyond the area between the radar and the decoy systems. This phenomena can be used in radar systems of ships and warships, to guide the ARMs outward the ship/warship. Ships generally counter anti-radiation missiles with decoy systems based on rockets, such that a rocket is launched from the deck of the ship after detection of anti-radiation missile. This system causes serious constraints, for example, in the seating location of the rocket launcher and with reduction in the number of rockets that can be carried.

The proposed system avoids these issues by providing a surviving decoy that guides the missile outside the area of concern. To our knowledge, the current literature on decoys and decoy systems has not mentioned the concept of the ability of decoy to guide anti-radiation missiles out of the radar-decoy area. The concept can be proved via scenarios that imagine its use with a fleet.

Consider a ship with a length of 100 m and an anti-radiation missile that is 2 km far from it. Setting \(\phi = 170^\circ\), the decoy and radar systems cause an error angle of about 6.5 degrees in the monopulse system tracker, causing the intercept site to be 159 m outside of the area occupied by the ship.
CONCLUSION

In this article, a novel method was proposed that uses survival decoys against anti-radiation missiles. In this method, the controlled phase and amplitude of the transmitted signal can counter the monopulse tracker system of anti-radiation missiles and guide them to a safe zone outside of the radar-decoy area. This method is specifically useful for naval applications, because the radar and the decoy are both located on the ship and the missile should not be guided to a point between them. Simulations show that this method can move the intercept point of anti-radiation missiles outside of the zone between the radar and the decoy systems. In the previous methods, the missiles impact the area between the radar and the decoy, with subsequent decreases in the reliability of its performance against anti-radiation missiles.

REFERENCES


