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Analysis of Cross-eye Jamming

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Abstract. A strict and comprehensive analysis of cross-eye jamming on an amplitude-comparison monopulse radar system is presented. It considers the implementation of cross-eye jamming and the form of monopulse antenna patterns that based on phased array antennas, the approximations limit the validity of other analyses are removed. The results show that under certain conditions, a monopulse radar system can be deceived more easily and the tolerances required to induce large angular errors can be looser than suggested by conventional analysis. Furthermore, the tolerances required in side lobes are greater than in main lobe, and the settling angle can no beyond two cross-eye jammer antenna elements under certain configuration of radar antenna.

Keywords: Cross-eye jamming, electronic warfare, electronic countermeasure, monopulse radar, radar tracking.

1. Introduction

Cross-eye jamming is an onboard electronic counter measures (ECM) used to induce an angular error in the radar that utilizing monopulse tracking system for angle measurement [1]-[4]. Cross-eye jamming system works by employing two spatially separated jamming sources, both sources act as repeater-type jammers transmit out of phase signals that make the target spatially removed from its true position. [1]-[6].

Different ways have been used to analyze cross-eye jamming on a monopulse radar system. The effect of cross-eye jamming is generally considered as a *distortion of the wavefront* incident on the antenna [7] or a change in the direction of the incident *Poynting* vector [8]. Cross-eye jamming has also been analyzed using *first-order Taylor approximations* to either the sum and different channel antenna patterns or the lobes of an amplitude-comparison tracking radar system [9], [10]. Some limitations are induced in these analyses. First limitation is that antenna is assumed to be *infinitesimally small* (either directly or indirectly), the other limitation is approximations to the lobes, and another limitation is that cross-eye implementation is ignored. Recently, an *extended analysis* of cross-eye jamming on phase-comparison monopulse system [2] has been published by W.P. du Plessis, it overcomes the approximations inherent in analysis.

In this paper, an analysis of cross-eye jamming on amplitude-comparison monopulse radar system that use electronically steered phased array antennas is presented. The analysis takes the implementation of cross-eye jamming and the form of monopulse antenna patterns that based on phased array antennas into consideration, and overcomes the limitations of conventional analyses. Theoretical analysis is represented in Section II, simulation and analysis on results are done in Section III, and a brief conclusion is provided in Section IV.

2. Theoretical analysis

2.1. Antenna patterns

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A planar phased array antenna is a two-dimensional configuration of antenna elements arranged to lie in plane, the planar array may be thought of as a linear array of linear arrays [11]. Most phased arrays of interest for radar are planar, but in this section it is started with *one-dimensional linear array* as the model since it is simpler to analyze.

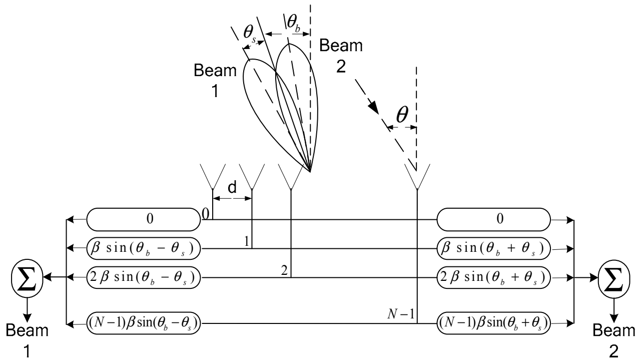

Fig. 1. Configuration of linear array antenna patterns used in amplitude-comparison monopulse system. It employs two groups of phase shifters and adders to form two monopulse beams, and an exact monopulse processor is assumed for further signal process.

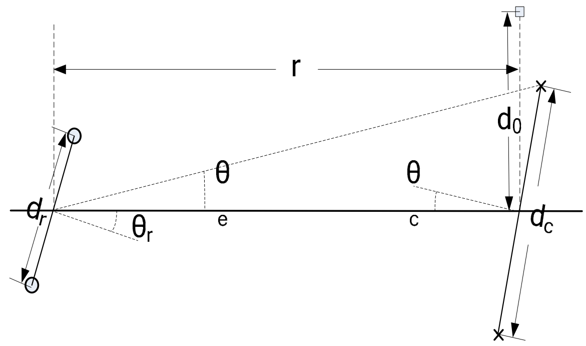

Fig. 2. The geometry of a cross-eye jamming scenario. The phase centers of the radar and jammer antenna elements are denoted by circles and crosses respectively, and the position of apparent target is shown by a square.

Considering the linear array antenna used in amplitude-comparison monopulse system as shown in Fig.1.The linear array is made up of N elements equally spaced a distance d apart. The elements are numbered from 0 to $N-1$ according from left to right, and element 0 is taken as the reference with zero phase. The pattern of a linear array can be derived from its excitation by giving [11], [12]

$$G(\theta)=\frac{\sin(N\beta d\sin\theta/2)}{N\sin(\beta d\sin\theta/2)} \quad (1)$$

Where θ is the angle measured from the normal to the antenna, and $\beta=\frac{2\pi}{\lambda}$ is the free-space phase constant, λ is wavelength of signals.

One-dimensional linear array monopulse antenna produces two beams that is constructed by two groups of phase shifters and adders [13] as shown in Fig.1.Considering when the boresight of the beam scans in angle θ_0 from the normal to antenna, its 3-dB beamwidth increases as $1/\cos(\theta_0)$ .The patterns of beam 1 and beam 2 can be written

$$G_1(\theta)=\cos(\theta_b-\theta_s)\frac{\sin[N\beta d(\sin\theta+\sin(\theta_b-\theta_s))/2]}{N\sin[\beta d(\sin\theta+\sin(\theta_b-\theta_s))/2]} \quad (2)$$

$$G_2(\theta)=\cos(\theta_b+\theta_s)\frac{\sin[N\beta d(\sin\theta+\sin(\theta_b+\theta_s))/2]}{N\sin[\beta d(\sin\theta+\sin(\theta_b+\theta_s))/2]} \quad (3)$$

Where θ is the angle measured from the boresight, θ_b is the direction of boresight measured from the normal to the antenna, θ_s is the squint angle.

Then the gain of the sum channel and different channel can be derived from $G_1 \pm G_2$.

2.2. Cross-eye analysis

Consider the cross-eye jamming scene shown in Fig.2.The phase centers of the radar and jammer antenna elements are denoted by circles and crosses respectively, and the position of the apparent target is shown by a square. d_r and d_c are the spacing of the phase centers of the radar antenna elements and cross-eye jammer antenna elements respectively, θ_r and θ_c are rotation of the radar system and jammer system measured from their perpendicular direction to the line links the center of radar antenna to the center of jammer, r is the range from the center of the radar antenna to the center of jammer, θ_e is half the angular separation of the jammer antenna elements as seen by the radar, d_0 is the linear distance from the center of jammer to the position of the apparent target. The underlying principle of cross-eye jamming is that the radar is not able to resolve the individual jammer antennas that implies $r >> d_c$.

The monopulse system uses sum-channel for transmitting and uses sum and different-channel for receiving. The different-channel return is normalized by the sum-channel return during signal processing, so the effects of any common factors are removed. A cross-eye jammer is introduced means that the entire signals received at one jammer element are retransmitted at the other jammer element after some delay. Assuming that the signals pass the cross-eye jammer from top antenna element to the bottom antenna element has an amplitude gain of a and a phase shift of φ relative to the signals pass the cross-eye jammer from the bottom antenna element to the top antenna element. The signal received by the radar in sum-channel and different-channel will be

$$S_\Sigma = G_\Sigma(\theta_r - \theta_e)G_a(\theta_a - \theta_e)G_a(\theta_a + \theta_e)G_\Sigma(\theta_r + \theta_e)(1 + ae^{j\varphi}) \quad (4)$$

$$S_\Delta = G_\Sigma(\theta_r - \theta_e)G_a(\theta_a - \theta_e)G_a(\theta_a + \theta_e)G_\Delta(\theta_r + \theta_e) + ae^{j\varphi}G_\Sigma(\theta_r + \theta_e)G_a(\theta_a + \theta_e)G_a(\theta_a - \theta_e)G_\Delta(\theta_r - \theta_e) \quad (5)$$

Where $G_a(\theta_r \pm \theta_e)$ are the gains of the top and bottom cross-eye jammer antenna in the direction of the radar antenna elements.

An exact monopulse processor forms its error signal by [10]-[13]

$$E(\theta) = \mathrm{Re}\{\frac{S_\Sigma \cdot S_\Delta^*}{S_\Sigma \cdot S_\Sigma^*}\} = \frac{G_\Sigma(\theta_r - \theta_e)G_\Delta(\theta_r + \theta_e) + a^2 G_\Sigma(\theta_r + \theta_e)G_\Delta(\theta_r - \theta_e)}{G_\Sigma(\theta_r + \theta_e)G_\Sigma(\theta_r - \theta_e)(1 + a^2 + 2\cos\varphi)}. \quad (6)$$

Where $E(\theta)$ is the monopulse error. There is no $G_a(\theta_r \pm \theta_e)$ in equation (6) means that the gain of cross-eye jammer does not affect the induced angular error what is consistent with analysis on a phase-comparison monopulse system that is analyzed by W.P. du Plessis [2].

3. Simulation and analysis

Fig.3 gives the monopulse error plotted against radar angle θ .Parameters used for simulation is typical of a missile threat an aircraft, $d = 0.5\lambda$ and $N = 23$ make 3-dB beamwidth= 4.4^0 approximately, $\theta_e = 0.15^0$, $\theta_s = 0.44^0$, θ_r=0^0 , θ_b=0^0 , and the two dots on the horizontal line at 0 indicate the position of two jammer antenna elements. The parameters a and φ used in simulation are given with their cross-eye gain in the legend of Fig.3.

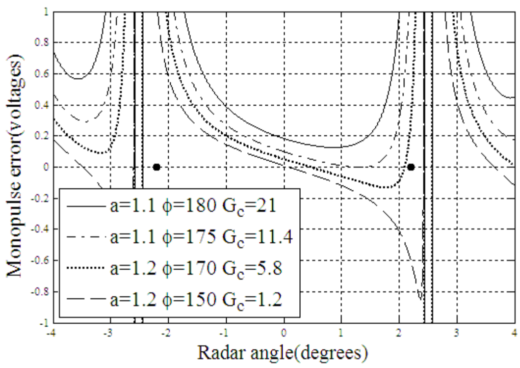

Fig. 3. Monopulse error produced by a monopulse seeker when a missile threats an aircraft.

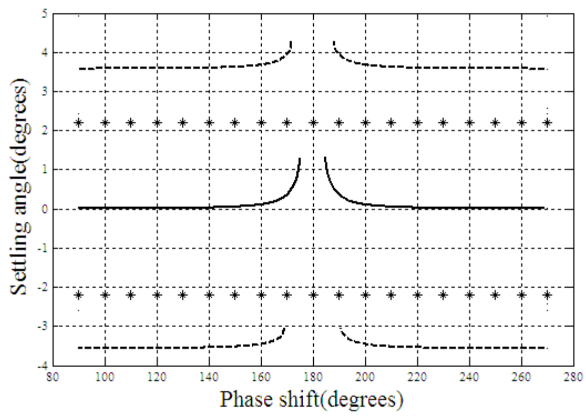

Fig. 4. Settling angle varies with the phase shift.

Fig.3 shows a case where the cross-eye gain is small, the zero crossing of monopulse error is expected to approach the center of the jammer means the settling angle is small, that is why cross-eye gain is defined. The curves corresponding to $a = 1.2$, $\varphi = 170^0$ and $a = 1.2$, $\varphi = 150^0$ are seen to have more than one zero crossing near the origin, but only the zero crossing nearest the origin are stable because the sign of the monopulse error will tend to drive the radar away from the other zero crossing. When $G_c = 11.4$, the curve is tangent to the vertical line at 0 rather than cross it. An important and interesting characteristic of the $G_c = 21$ case is that the monopulse error never becomes zero and always to be positive means the settling angle doesn't exist and the radar will track nothing. This conclusion is different to the conventional analyses.

Fig.4 and Fig.5 plot the settling angle varies with the phase shift when $a = 1.1$ and relative amplitude when $\varphi = 180^0$ by calculating contour plots of monopulse error respectively. The two horizontal lines with stars indicate the position of two cross-eye jammer antenna elements, the solid curves are the settling angle line in main lobe and the dash curves are the settling angle line in the first side lobes beside the main lobe.

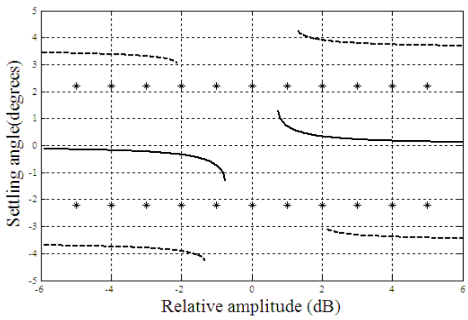

Fig. 5. Settling angle varies with the relative amplitude. Settling angle increases with relative amplitude approaches $0dB$ which also lead to cross-eye gain increase

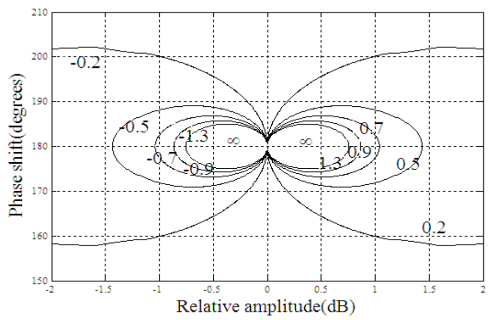

Fig. 6. Contours of monopulse error analyzed in this text. Tolerance required to induce large angular error is great which implies that the monopulse radar system can be deceived easily.

Fig.4 and Fig.5 show that the settling angle increases with the phase shift approach 180^0 or relative amplitude approach $0dB$ both of which lead to cross-eye gain increase. The solid curves in Fig.4 with a relative amplitude of 1.1 end abruptly at relative phase shift of 5^0 from 180^0 because the settling angle does no exist in this case, and the dash curves end abruptly at relative phase shift of 8.1^0 from 180^0.The solid curves in Fig.5 with a phase shift of 180^0 end abruptly at relative relative-amplitude of $0.8dB$ from $0dB$,and the dash curves end abruptly at relative relative-amplitude of $2.1dB$ from $0dB$.It shows that the range phase shift or relative amplitude vary while the settling angle doesn't exist is greater in side lobes than in main lobes. The max angular error is 1.3^0 about 30% of the 3-dB beamwidth approximately rather than 60% of the 3-dB beamwidth as calculated by Lothes [14] and Golden [15]. It implies that the apparent target produced by cross-eye jammer always between the two cross-eye jammer elements, what is greatly different from the conventional analyses suggested that the apparent target beyond the two cross-eye jammer elements. The reason for this difference is the configuration of monopulse system shown in Fig.1, the result tends to be equal when linear array antenna instead of two horn antennas.

The amplitude and phase matching between signals that through the cross-eye jammer in two directions is required to achieve a specified cross-eye gain for a specified angular error. The contours in Fig.6 and Fig.7 are plotted giving a clear graphical representation of the relationship between the matching and angular error in main lobes. Fig.6 is plotted using analysis in this text, and Fig.7 is plotted using linear fit analysis for comparison.

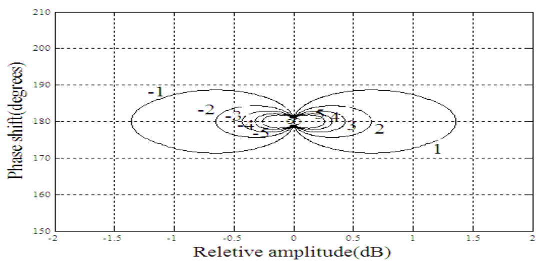

Fig. 7. Contours of monopulse error analyzed by linear fit analysis. Tolerance required to induce large angular error is strict which implies that the monopulse radar system is difficult to deceive.

The case settling angle doesn't exist can be seen as the settling angle to be infinite.Fig.6 and Fig.7 shows that the tolerance required to induce large angular error is greater analyzed by analysis in this text than by linear fit analysis which implies that the monopulse radar system can be deceived more easily than suggested by conventional analyses. Furthermore, what can be estimated is that the tolerance in side lobes is greater than in main lobe when Fig.4 and Fig.5 are considered.

4. Conclusion

An strict analysis about cross-eye jamming is presented that considers the implementation of amplitude-comparison monopulse radar system based on phased array antenna and cross-eye jamming signal processing, removing the approximations used in conventional analyses. Analysis concludes that the fact that monopulse error will never become 0 under certain conditions implies that cross-eye jamming can deceive the monopulse radar system more easily than suggested by conventional analyses. The tolerances requirements to induce large angular errors are not as strict as the literature suggests, and the tolerances required in side lobes are greater than in main lobe. Furthermore, cross-eye jammer antenna elements patterns do not affect the induced monopulse error, and the settling angle can no beyond two cross-eye jammer antenna elements under the configuration of linear array antenna patterns described in Fig.1.The conclusions can be used on electronic attack and electronic protection.

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