Research on MIMO Radar Based on Orthogonal Signal in the Present of Non-Ideal Factor

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Abstract: Non-ideal factors of transmitting signal are known as a kind of restriction to the performance of radar, especially the ability of finding the weak target. In this paper, the performance of MIMO radar in the aspect of weak target detection is researched. Firstly, the theory model of MIMO signal is presented. And then, a simulation system based on orthogonal signal is established. In this simulation platform, the performance of MIMO radar and phased array radar are studied. Simulation results show that for the same receiver limiting factor, the statistical error probability of MIMO radar is much lower than traditional phased array mode.

Keywords: MIMO radar, non-ideal factor, simulation system, target detection.

1. INTRODUCTION

Radar theory and technology is a rapidly developing field that has seen tremendous progress, challenging the traditional concepts and architecture to be continuously updated by a number of new radar systems. MIMO (Multiple Input Multiple Output) is a new radar system proposed in recent years, and it has attracted wide attention from scholars. Derived from the communication field, the MIMO technology incorporates a plurality of antennas to transmit different signals. This is an operating mode where each of these antennas is able to independently receive target echo. MIMO radar has come into the vision of people, with the related theoretical issues now under the thematic discussions [1-4]. At this stage, the research work on the MIMO radar is focused on the theoretical studies. Literature on MIMO radar presents a wide coverage, including target detection and location, parameter identification, signal design and fuzzy functions, *etc*. [5-9]. Nevertheless, the radar array model in the study of MIMO is limited to two major forms: the intensive radar and the distributed radar. Intensive MIMO radar is mainly reflected by digital array [1, 4] and the compact array proposed by Li *et al*. [7]. Distributed MIMO radar is represented by Fishler and Haimovich, who used a wide area of sparse lineup for introducing the spatial diversity to improve the radar performance [2, 10]. Compared with the distributed MIMO radar, the intensive form is closer to the reality of projects, easy to be implemented. Furthermore, it boasts some of the signal processing methods for the conventional phased array, such as matched filtering, digital beamforming, and dynamic target detection.

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2. SIGNAL MODEL OF THE MIMO RADAR

The MIMO radar provides a multiple transmit antenna array, consisting of several sub-arrays. The internal antenna of each sub-array transmits the same signal, same as the conventional phased array. Transmitted signals can be formed into beams in the space. Due to the small number of sub-array transmitting antenna, the formation of beams is yet characterized by larger width and lower gain. Signal transmission between the sub-arrays is mutually orthogonal to satisfy the following conditions.

$$\int_0^{T_p} s_i(t)s_j(t) = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases} \tag{1}$$

where, $s_i(t)$ is the signal transmitted by the i -th sub-array, and T_p is the duration of the radar signal. There are many types of quadrature signals, such as frequency-division chirp signal, the frequency-encoded signal, phase-coded signals, etc. In this paper, the proposed simulation system was applied for the simulation on each of these three orthogonal signals. The mostly used signal was frequency-division chirp signal, which can be expressed in Eq. (2):

$$s(t) = \sqrt{P_t} \cdot \exp[\mathrm{j}(2\pi f_m t + \frac{1}{2}\mu t^2)], \quad 0 \le t \le T_p \tag{2}$$

where, P_t is the power of a single transmit antenna; $\mu = B_s / T_p$ is the chirp rate; f_Δ is the frequency interval between the transmitted signals, usually chosen as $f_\Delta = B_s$; f_m is the starting frequency of the m -th LFM signal, fitting

$$f_m = f_0 + m f_\Delta, \quad m = 0, \cdots, M-1$$

Transmitted by the array, the signals reached the object, and were reflected back to the receiver antenna array. Each

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antenna separately received echo signal that were processed separately. Here the conventional radar techniques may take on the job of signal processing. The first step was to passes through the matched filter to isolate the signal components transmitted by each sub-array. Then, a plurality of digital beams was formed to cover the entire space of transmitting beams. Subsequently, the output signal of each beam was detected on moving targets to obtain the possible speed of every target. The final detection was handled over to the CFAR. The final result of the detection indicators was exported, such as distance, direction, speed and other parameters. This work aimed to investigate the impact of radar signals emitted, including non-ideal factors and the strong clutter, on the MIMO radar and the radar target detection with a phased array.

2.1. Non-Ideal Factors of the Signal Emitted

For a radar system, non-ideal factors may arise from the instability of transmitter units, such as the signal source, traveling wave amplifier, magnetron oscillator, crossed-field tube amplifier, timer and the like. Characteristically, the instability of amplitude and frequency is common, where spurious signals may particularly bring a great impact on signal detection, causing the detector to produce a false target. The following section gives a detailed analysis on the impact of such non-ideal factors on the MIMO radar.

Signal lines with spurious transients output by the radar transmitter can be expressed as

$$s(t)=E_0 e^{j(2\pi f_0 t+\frac{1}{2}\mu t^2)}+b_m e^{j(2\pi(f_0+f_m)t+\frac{1}{2}\mu t^2)} \tag{3}$$

In Eq. (3), the first term is the desired signal, and the second term is spurious component. Signals emitted by the MIMO radar sub-array were independent and spurious, uncorrelated to each other, not to produce an array of gain. Compared to a phased array, the transmitting radar signals were all in the same, they came from the same source, being equally spurious to bring out an array of gain. Through the Bessel expansion, (3) can be expressed as:

$$\begin{aligned} s(t)=E_0 e^{j(2\pi f_0 t+\mu t^2)}\cdot[J_0(b_m)+ \\ \sum_{n=1}^{\infty} J_n(b_m)(e^{jn2\pi f_m t}+(-1)^n e^{-jn2\pi f_m t})] \end{aligned} \tag{4}$$

Being less spurious, (4) can be approximated as

$$\begin{aligned} s(t)&=E_0 e^{j(2\pi v_0 t+\mu t^2)} \\ &+\frac{1}{2}b_m E_0 e^{j(2\pi f_0 t+\mu t^2+j2\pi f_m t)} \\ &-\frac{1}{2}b_m E_0 e^{j(2\pi f_0 t+\mu t^2-j2\pi f_m t)} \end{aligned} \tag{5}$$

This signal is output through the matched filter

$$\begin{aligned} g(t)&=E_0{}^2 e^{j\pi(kt(T-t)-\mu t^2)}\cdot\frac{\sin(\pi\mu t(T-|t|))}{\pi\mu t(T-|t|)}(T-|t|) \\ &+\{E_0\cdot b_m e^{j\pi((f_m-kt)(T-t)-\mu t^2)} \\ &\cdot\frac{\sin(\pi(f_m-\mu t)(T-|t|))}{\pi(f_m-\mu t)(T-|t|)}(T-|t|)\} \end{aligned} \tag{6}$$

In Eq. (6), the second term shows a false target. False targets of the transmitting signals by the phased array radar appeared in the same position. Their coherent superposition generated a strong false echo. False targets of the transmitting signal by the MIMO radar were generated not in the same position, resulting in multiple small false targets, posing less impact on the real target detection.

2.2. Impact of Strong Clutter on Target Detection

In the presence of strong clutter, MIMO radar produced a weaker echo than the phased array radar. An echo clipping is usually given prior to processing by radar. In receiving, the same clipping threshold was set for this purpose. When using the phased array radar, clipping distortion (saturation distortion) would occur, but this did not happen to MIMO radar. Clipping distortion may result in distortion of the received signal and the spurious spectrum to be broadened. These adverse consequences would affect the detection performance of targets. Simulation experiments were performed to compare the impact of the same clipping that may have on both types of radars.

3. SIMULATION PLATFORM OF MIMO RADAR BASED ON ORTHOGONAL SIGNAL

A simulation system is usually equipped with some features, including: phased array mode, the quadrature signal radar mode, influence of environmental noise on the detection, non-ideal parameters of radar system, anti-interception performance of radar, radar signal processing (matched filter, digital beamforming, MTD, CFAR, *etc*.). Fig. (**1**) shows the specific process.

The module Waveform Generator is used to generate the transmitted waveform of radar; the module Emitting Array is there for simulating the transmitter array of radar and the transmitted signals of various array elements; the two modules of Transmit Propagation Channel and Receive Propagation Channel are prepared to simulate the space propagation and propagation attenuation of the electromagnetic wave; the module Intercepts Receiver is designed to simulate the basic radar reconnaissance receiver for testing the LPI performance with radar; simulation modules Target.

Clutter and Interference are, respectively, deployed to emulate the target echo, noise clutter (including land clutter and sea clutter) and interference. As to the module Receiving Array, it works for the simulation of receiving array with radar; the module Receiver is installed for processing the radar receiver (including mixing, zoom) ;

Signal Processor is applied for matched filtering, digital beamforming, and the algorithms MTD, CFAR in simulation; Data Processing is responsible for target tracking and processing algorithms; the last Radar Display module aims to display the results of target detection and target parameter estimation.

Based on orthogonal signal, MIMO radar is built with a simulation platform by use of MATLAB 7, where both simulation interface and parameter input interface are implemented using Visual C ++. This makes it easy to visually modify parameters with processing effect. The following main modules are here described in details.

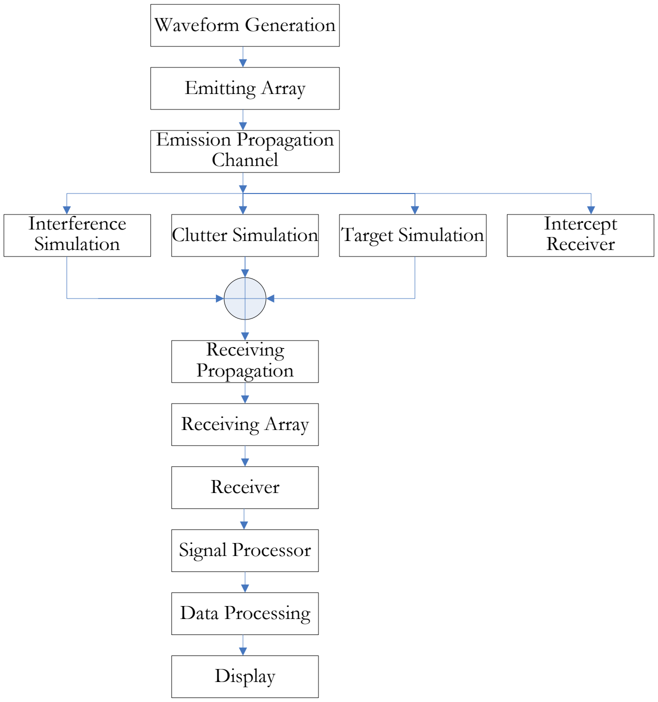

Fig. (1). Flowchart of the radar simulation system.

3.1. Module of Signal Generation

The Signal Generation is a sub-module for the simulation system, mainly applied to the waveforms in the phased array and MIMO modes. Under the phased array mode, each array element transmitted the same form of the waveform, while the MIMO mode worked with each array element transmitting mutually orthogonal waveforms. We mainly considered the Orthogonal Frequency Division Multiplexing based on Linear Frequency Modulation (OFDM LFM), for which the MATLAB language was applied to implement such a signal form, as shown in Eq. (2). Simulation parameters included the number of transmitting antennas, pulse width, sampling frequency, signal bandwidth, carrier frequency, interval of signal frequency, signal power as well as non-idealities of the transmitted signal (mainly the spurious signals). In the system, the signal data generated was written to disk file for the use by subsequent modules.

3.2. Module of Target Environment

In the first place, this module received data sent by the last module, and then to determine how the target environment provided modulation processing on the transmit signal, and finally to generate the data of signal received for the processing by next module. In the target environment module, three signals were observed: Target, clutter and noise. Where the target signal was generated through the simulation of four Swerling models. First, to calculate the echo power under the radar equation:

$$P_r = \frac{P_t G_t G_r \lambda^2 F_r^2 F_t^2}{(4\pi)^3 R^4 L} \tag{7}$$

where, P_r is power of the received signal (antenna end); P_t is power of the transmit signal (antenna end); G_t is the power gain of transmitting antenna; G_r is the power gain of receiving antenna; λ is the radar wavelength; F_t is the propagation factor of pattern from transmitting antenna to target; F_r is the propagation factor of pattern from target to receiving antenna; R is distance between target and radar; σ is the cross section of target effective with radar; L is the various propagation gain and loss factors not present in the free space, such as the common absorption, diffraction, interception, refraction and multipath, etc. If P_r is pre-detection power of the received signal, then L also includes pre-detection factor of system loss. To sum up, the simulation flow of radar targets is as follows:

Reading the transmission signal to generate the echo data $\mathrm{sig(t)}$;

Calculating the Doppler shift for the modulation into the signal echo;

$$\mathrm{f_d} = \frac{2v}{\lambda} \text{ ; } \mathrm{Target(t)=sig(t)\times f_d}$$

Under radar equation, calculation was made to obtain the power attenuation of the echo signal arriving at the receiving antenna;

Power of the transmitted signal is multiplied by the received signal;

Calculating the delay of the round-trip distance for waves to reach the target;

$$\tau = \frac{2R}{c}$$

Delay of the received signal

$\mathrm{Target(t)=Target(t-}\tau)$

Echo signal is multiplied by the steering vector for the direction of the transmit array to obtain the received signal of a target.

Clutter signal is generated in a manner similar to target echo. The system used the transformation of zero memory nonlinearity (ZMNL) to achieve three different types of clutter: Rayleigh distribution, Weibull distribution and the lognormal distribution, being able to simulate the radar work in different environments.

Noise generation was based on the bandwidth of received signal. We introduced the additive white Gaussian noise, with noise power being calculated according to (8):

$$P_n = N_0 B_n = kTF_n B_n \tag{8}$$

Eventually, this module produced target echo, clutter and noise, all being added as the resulting signals, which were written to disk file for the next module.

3.3. Module of Received Signal Processing

This module first read the incoming data from the target environment module. A matched filter was then utilized to separate the received signals from each antenna, obtaining each component of the transmission signal. Subsequently, the DBF technology took over the job to promote the multiple digital beamforming. For each beam the target speed was detected using MTD; Finally, detection threshold was given in line with the CFAR to detect targets. Specific steps are shown in Fig. (**2**).

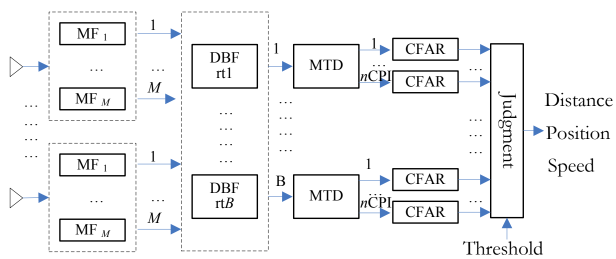

Fig. (2). Flow of signal processing.

3.4. Module of Display

After the end of the system simulation, the system read out from the MATLAB platform all the needed data, which would then be converted into the format that could be recognized by VC ++, and saved to the specified file. Based on these data, the C language was used to draw the final test results.

4. SIMULATION RESULTS

In this section, the simulation system developed above is taken for comparison study of phased array radar and MIMO radar under the same conditions with respect to differences in target detection performance, with a particular focus on non-ideal factors of anti-transmitted signal and the detection capability of weak targets in the presence of clutters.

In the first experiment, as shown in Fig. (**3**), two targets with the same speeds were set in a distance of 20 km and 40 km, respectively. As the transmitted signal contained the spurious intensity of -20dB, 20 km target might generate a false target strength that was stronger than 40 km target, and the detector would produce false targets. Comparatively, similar cases did not occur to MIMO radar.

In the second experiment, as shown in Fig. (**4**), target detection was performed in a strong clutter environment. A set of simulation experiments were organized accordingly. For the phased array mode and the MIMO mode, the receiving clipping threshold was defined in a range of $0.2\times10^{-6} \sim 2.8\times10^{-6}$. Each clipping threshold was given 50 times of Monte Carlo simulation, followed by generating the curve of the probability of detecting errors that changed with the receiving clipping factor (defined as a ratio of the receiver clipping threshold *vs* the maximum amplitude of the received signal in the phased array mode).

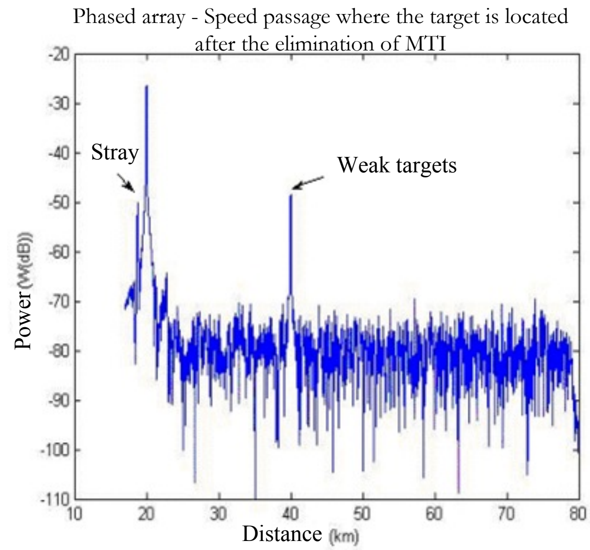

Fig. (3). Detection result by the phased array radar - false targets of the strong targets higher than the weak targets.

The simulation results are shown in Fig. (**5**). Obviously, for the same receiver clipping factor, MIMO presented a statistical error probability that was lower than phased array. In the case that the receiver clipping factor was greater than 0.4, the error probability of the MIMO mode has been stabilized at 5% or less, while the error probability of the phased array mode was still at a relatively high level.

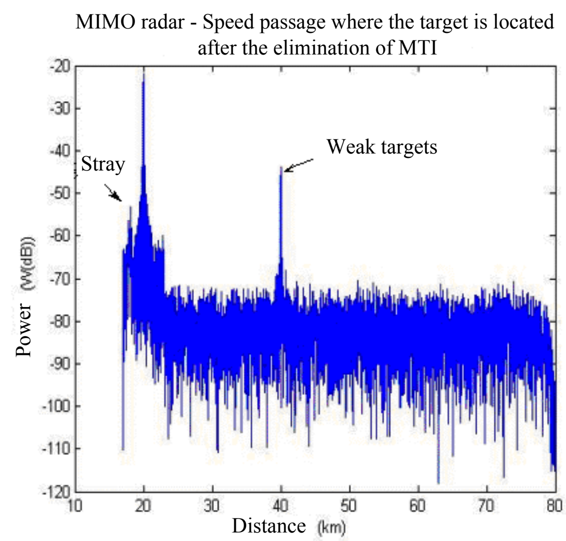

Fig. (4). Detection result by the MIMO radar - false targets posed on impact.

CONCLUSION

Theoretically, this paper discussed the non-ideal factors of the transmitted signal and the strong clutter with their influence on target detection, and then through the establishment of simulation systems, a comparative study was made on the MIMO radar and the phased array radar.

The simulation results showed that the performance of MIMO radar was quite impressive.

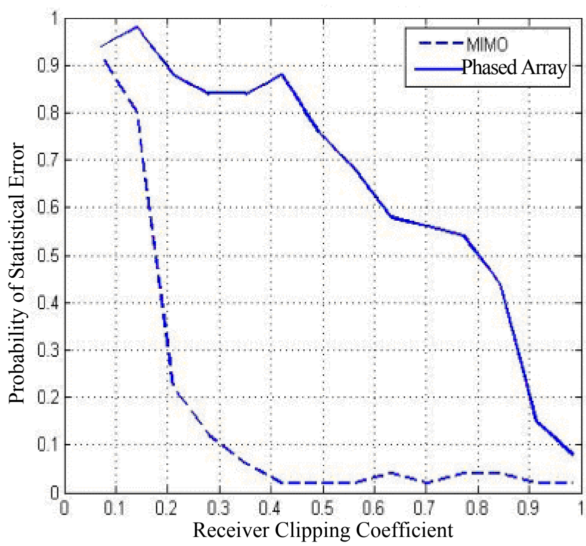

Fig. (5). Receiver clipping factor - probability curve of statistical errors.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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Declared none.

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