ANALYSIS AND SIMULATION OF ANTI-JAMMING TECHNOLOGY OF PHASE CODED COMPRESSED SENSING RADAR

[1]Nazim Hussain, [2]Han Zhuangzhi, [3]Zhao Yang
Army Engineering University of PLA, Shijiazhuang Campus, Hebei Province, China
[1]nazim_hussain88@yahoo.com, [2]1492922091@qq.com, [3]zhaoyang_oec@foxmail.com

ABSTRACT: *In order to ensure operational effectiveness in a complex jamming environment, it is necessary for modern radars to have an efficient anti-jamming system. Phase coded signal is a very important type of signal in Compressed Sensing Radar (CSR). Phase coded signals have more complicated signal structures and thus, are difficult to be accurately detected and analyze by the enemy's Electronic Support Measures (ESMs). Therefore, phase-coded signals are very important to improve the anti-jamming ability of CSR. Aiming at the prominent problems of phase coded CSR in the process of electronic countermeasure and electronic counter countermeasure, this thesis tries to optimize the phase coded signal waveform to improve its anti-jamming ability, to improve the resolution of target and to reduce the probability of being found by enemy's electronic reconnaissance equipment.*

Key Words: Anti-jamming system, Phase coded signal, Compressed Sensing Radar (CSR), Orthogonal Matching Pursuit (OMP), Genetic Algorithm (GA), Electronic Countermeasures (ECM)

INTRODUCTION

Electronic jamming, especially active jamming, is a major factor affecting the normal operation and performance of the radar system. Currently, there are mainly two ways for radar anti-active jamming: one is to improve the anti-jamming capability through radar network, and the other is to improve the anti-jamming capability of single-station radar. The latter is the basis for improving the anti-jamming capability of the radar system. In the process of confronting electronic warfare equipment, the traditional single-station radar is usually at a disadvantage, mainly for the following three reasons:

One is that in the process of electronic countermeasures, the attenuation rate of radar signals is much faster than that of jamming signals. The power of jamming signals received by the radar is inversely proportional to the square of the distance between the radar and the jammer, while the power of the echo signal received by the radar is inversely proportional to the fourth power of the distance between the two, which makes the aircraft jamming pods easier to produce false targets and reduce detection ability of radar. The strong jamming signal makes the radar unable to detect the targets [1]. Figure 1-1 is a brief schematic diagram of the reconnaissance process of radar signals by electronic reconnaissance equipment. Digital Radio Frequency Memory (DRFM) has developed rapidly, which greatly shortens the time between intercepting radar signals by electronic reconnaissance equipment and generating jamming responses, e.g. the response time of interval sampling repeater deception jamming can reach the nanosecond level. Hence self-defense jamming patterns are constantly enriched, due to which radars are facing serious active jamming threats[2, 3].

The second is the limitation of the signal processing system. Although the anti-electronic countermeasure capability of radar has been strengthened in recent years, the basis of radar is to first complete the detection and tracking of the target. This forces the radar to adopt traditional signal processing technology to limit the changing speed and scope of radar transmitted signal parameters, which limits the development of radar anti-jamming capabilities[4].

The third is that the radar equipment cannot perceive and respond to the jamming environment. Single-station radar equipment generally forms a closed-loop tracking control system in the process of target detection, but there is no closed-loop jamming sensing-signal emission anti-jamming system for active jamming [5].

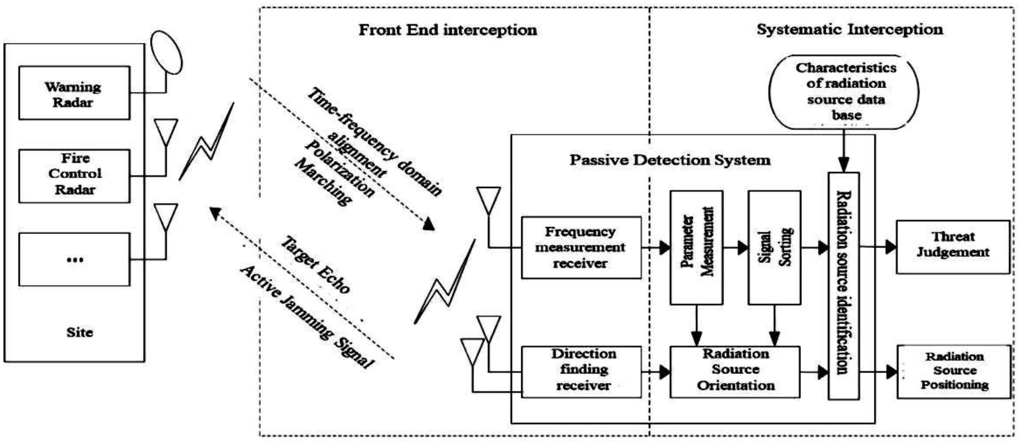

Fig. 1 Basic Working Process of electronic reconnaissance system

The sensing of jamming signals is usually coordinated through other weapon systems. This is related to the current radar system design and signal processing capabilities. However, the improvement of the anti-active jamming ability of radar in the future battlefield requires the development of its own independent anti-jamming system [6, 7].

Although the current radar system has certain disadvantages in the electronic countermeasures process, there is a saying widely circulated in the field of electronic countermeasures: *there is no radar that cannot be jammed, and there is no jamming that cannot be countered*. Before the landing of ultra-new radars such as quantum radars, it is unrealistic for radars to completely get rid of jamming. However, radars can be improved to enhance the anti-jamming performance of radar equipment, to increase the difficulty for the enemy to interfere, and to limit jamming strategies, especially to improve the radar's self-defense capability of preventing the jamming signal from entering from the main lobe. The ability of countermeasures against jamming is an ability that can be dug deep and radars should have [8]. Aiming at the problems in the anti-active jamming process of traditional radars, in this thesis anti-active jamming technology of Compressed Sensing Radar (CSR) using phase-encoded signals based on the Compressed Sensing (CS) theory is focused. It can provide some new ideas for the design of new generation radar equipment [9].

The combination of CS theory and radar signal processing has natural advantages. The sparse scene of radar echo signals meets the basic requirements of CS theory for signal sparseness in a specific domain. This is the basic condition provided by the radar field for the practical application of CS theory; and CS theory points out that the sparse echo signal can be reconstructed in a way far lower than the Nyquist sampling rate, which reduces the radar's sampling requirements for the RF analog-to-digital converter and saves from unnecessary huge data storage problem. This advantage is gained by using CS theory for radar signal processing. CS theory and radar signal processing are combined with complementary advantages. CSR imaging, Multi-Input and Multi-Output (MIMO) CSR and other new system radars were also quickly born after the advent of the CS theory [10]–[12]. In addition, existing studies have shown that CSR can effectively solve the difficult problems in traditional radar signal processing such as sidelobe reduction, deblurring, high resolution, defective data recovery, and high-complexity signal processing, etc. The solution of these problems is beneficial to improve the anti-jamming ability of CSR from different perspectives and provides a great possibility for the application of CSR in the field of anti-active jamming [12, 13]. The reduction of the sampling rate allows the signal processing receiver of CSR to be no longer limited by processing the target echo signal. CSR can use the remaining sampling resources to sense the jamming environment, which coincides with the development direction of cognitive radar at this stage.

In summary, the traditional signal processing theory limits the methods and means of radar anti-active jamming to a certain extent. The anti-active jamming capability of radar needs to be improved on an urgent basis. CSR can not only significantly reduce the sampling rate, shifting the requirements on the wideband sampling of radiofrequency devices to the requirements of computing capabilities but also enable the radar to have a certain ability to perceive the current jamming environment, providing room for further improvement in anti-active jamming signal design and processing, etc. Therefore, the research to corresponding anti-active jamming methods to improve CSR's jamming identification and anti-active jamming capabilities are in line with the actual combat requirements of the development of radar equipment. The relevant research on CSR's anti-active jamming has important practical and guiding significance [14].

Jamming Strategy

A radar system is a complex and multifunctional integrated system. In the modern era, a quantitative estimate of the effectiveness of anti-jamming is vital to the assessment of risks and the probability of success. Data processing is always carried out in radar and the feasibility of using the existing signal processing resources of radar for intermittently sampling jamming strategy identification is one of the most commonly used methods of radar. The ability to distinguish between true and false targets of radar equipment is highly required. In this section, the manifestations of target echo signal and intermittent sampling jamming signal processed by matched filtering are deduced in the time domain. Phase coded signal is a very important type of signal in CSR. The processing output of the phase-coded signal has a large main lobe-to-sidelobe ratio over the binary signal of the same cone length. As phase-coded signals have a more complicated signal structure, thus, are difficult to be detected and analyzed by the enemy's Electronic Support Measures (ESMs). Hence, phase-coded signals are very important to improve the anti-jamming ability of CSR. Therefore keeping in view the benefits of phase coded signal, the feasibility of jamming strategy identification based on matched filtering results is analyzed, so as to provide the estimated value of jamming signal at the current moment, for the optimization of CSR code pattern of phase coding in the background of active jamming.

Intermittent Sampling Jamming Strategy Identification

This section will discuss the feasibility of using the existing signal processing resources of radar for intermittent sampling jamming strategy recognition. Intermittent sampling jamming is one of the most common methods to counter radar of phase encoding systems. The development of the DRFM technique makes jamming equipment quickly copy and transmit jamming signals in one radar pulse. The jamming signal can get some signal processing gain, and the changes of slicing and repeater strategy can produce one or more false targets. Thus the ability of radar equipment to distinguish between true and false targets is highly required. Moreover, its transmitting time is usually controlled within the current pulse time, so it is difficult for radar to estimate the power spectrum of such jamming without target echo. In this section, the manifestations of target echo signal and intermittent sampling jamming signal processed by matched filtering will be deduced in the time domain. And the feasibility of jamming strategy identification based on matched filtering results will be further discussed, so as to provide the estimated value of jamming signal at the current moment, for the optimization of CSR code pattern of phase coding in the background of active jamming [135].

Analysis on the Principle of Phase Encoding Signal Waveform Matching

Let the expression of the phase coded signal be

$$s(t)=a(t)\exp\left[j\varphi(t)\right]\exp\left(j2\pi f_0 t\right),\ 0\le t\le T \qquad (3\text{-}1)$$

where, $\varphi(t)$ is a multiphase coding function, T is the pulse width, f_0 is the carrier frequency, and

$a(t)$ is the amplitude at the corresponding time. At this point, the complex envelope of the signal can be expressed as

$$s(t)=A(t)\varphi_m,\ 0\le t\le T \tag{3-2}$$

In the formula, φ_m is the phase value corresponding to the m^{th} symbol. When the echo signal arrives, it is necessary to detect and filter the echo signal and convert the signal down to zero-IF frequency. It is assumed that the complex envelope of the output is approximately rectangular at this time without loss of generality

$$A(t)=\frac{1}{\sqrt{L_s\tau_0}} \tag{3-3}$$

Where, L_S is the code length, and τ_0 is the code width. Substituting Equation (3-3) into Equation (3-2) can be obtained

$$\begin{aligned}s(t)&=\frac{1}{\sqrt{L_s\tau_0}}\sum_{m=0}^{L_s-1}\varphi_m\text{rect}\left(\frac{t-\tau_0/2-m\tau_0}{\tau_0}\right)\\&=\left[\frac{1}{\sqrt{\tau_0}}\text{rect}\left(\frac{t-\tau_0/2}{\tau_0}\right)\right]*\left[\frac{1}{\sqrt{L_s}}\sum_{m=0}^{L_s-1}\varphi_m\delta(t-m\tau_0)\right]\\&=u(t)*v(t)\end{aligned} \tag{3-4}$$

In the formula, $\delta(\cdot)$ represents impulse function, where the value of $u(t)=1/\sqrt{\tau_0}\cdot\text{rect}\left[(t-\tau_0/2)/\tau_0\right]$, and $v(t)=1/\sqrt{L_s}\cdot\sum_{m=0}^{L_s-1}\varphi_m\delta(t-m\tau_0)$. By match filtering the echo signal expressed by formula (3-4), the output signal can be obtained as follows

$$\begin{aligned}y(t)&=\int_{-\infty}^{+\infty}s(u)s^*(u+t)du\\&=\int_{-\infty}^{+\infty}s(u)s^*(t-(-u))du\\&=s(t)*s^*(-t)\\&=\left[u(t)*u^*(-t)\right]*\left[v(t)*v^*(-t)\right]\\&=R_u(t)*R_v(t)\\&=\sum_{n=-(L_s-1)}^{L_s-1}R_u(t-n\tau_0)R_v(n\tau_0)\end{aligned} \tag{3-5}$$

in which $R_u(t)$ and $R_v(t)$ are autocorrelation functions of $u(t)$ and $v(t)$, respectively. Substituting $u(t)$ into $R_u(t)$, it can be obtained that

$$R_u(\tau)=\int_{-\infty}^{+\infty}u(t)u(t+\tau)dt$$

$$=\begin{cases}1-\frac{\tau}{\tau_0} & ,0<\tau\le\tau_0\\ 1+\frac{\tau}{\tau_0} & ,-\tau_0<\tau\le 0\end{cases} \tag{3-6}$$

$$R_u(t-n\tau_0)=\begin{cases}1-(t-n\tau_0)/\tau_0, & 0<t-n\tau_0\le\tau_0\\ 1+(t-n\tau_0)/\tau_0, & -\tau_0<t-n\tau_0\le 0\end{cases} \tag{3-7}$$

If n is a positive number, then for a given value of n, t corresponds to n, and

$$n=\begin{cases}\lfloor t/\tau_0\rfloor, & t\ge 0\\ \lceil t/\tau_0\rceil, & t<0\end{cases} \tag{3-8}$$

Substitute $v(t)$ into $R_v(t)$, it can be obtained that

$$\begin{aligned}R_v(\tau)&=\frac{1}{L_s}\sum_{m=0}^{L_s-1}\sum_{k=0}^{L_s-1}\int_{-\infty}^{+\infty}\varphi_m\varphi_k\delta(u-m\tau_0)\delta(u-k\tau_0+t)du\\&=\frac{1}{L_s}\sum_{m=0}^{L_s-1}\sum_{k=0}^{L_s-1}\varphi_m\varphi_k\delta(t-k\tau_0+m\tau_0)\end{aligned} \tag{3-9}$$

Let $k=m+n$, the above equation can be simplified as

$$R_v(n\tau_0)=\frac{1}{L_s}\sum_{m=0}^{L_s-1-n}\varphi_m\varphi_{m+n},\ 0\le n\le L_s-1 \tag{3-10}$$

Equation (3-10) can be extended to $n\le 0$ in the same way

$$R_v(n\tau_0)=\begin{cases}\frac{1}{L_s}\sum_{m=0}^{L_s-1-n}\varphi_m\varphi_{m+n}, & 0\le n\le L_s-1\\ \frac{1}{L_s}\sum_{m=-n}^{L_s-1}\varphi_m\varphi_{m+n}, & -(L_s-1)\le n<0\end{cases} \tag{3-11}$$

Substitute formula (3-7), (3-8), (3-11) into formula (3-5), we can obtain

$$\begin{aligned}y(t)&=\sum_{n=-(L_s-1)}^{L_s-1}R_u(t-n\tau_0)R_v(n\tau_0)\\&=\begin{cases}\left(1-\frac{t-\lfloor t/\tau_0\rfloor\tau_0}{\tau_0}\right)\frac{1}{L_s}\sum_{m=0}^{L_s-1-\lfloor t/\tau_0\rfloor}\varphi_m\varphi_{m+\lfloor t/\tau_0\rfloor}, & t\ge 0\\ \left(1-\frac{t-\lfloor t/\tau_0\rfloor\tau_0}{\tau_0}\right)\frac{1}{L_s}\sum_{m=-\lceil t/\tau_0\rceil}^{L_s-1}\varphi_m\varphi_{m+\lceil t/\tau_0\rceil}, & t<0\end{cases}\end{aligned} \tag{3-12}$$

where $\left[1-\left(t-\lfloor t/\tau_0\rfloor\tau_0\right)/\tau_0\right]$ represents the matched filter output envelope with $\frac{1}{L_s}\sum_{m=0}^{L_s-1-\lfloor t/\tau_0\rfloor}\varphi_m\varphi_{m+\lfloor t/\tau_0\rfloor}$

amplitude less than 1， represents the normalized autocorrelation function of the waveform.

Recognition of Repeater Jamming Signals

The phase-coded signal is set as 127-bit M sequence, the code width is $1\mu s$, the pulse width is $127\mu s$, and the amplitude is 1. The jamming parameters of multiple groups of direct repeater jamming were set as follows: ① Pulse width of intermittent sampling τ=$10\mu s$, duty cycle 0.5;② τ=$10\mu s$, duty cycle 0.25;③ τ=$20\mu s$, duty cycle 0.5;④ τ=$20\mu s$, duty cycle 0.4. The normalized pulse pressure output simulation results are shown in Figure 3-4.

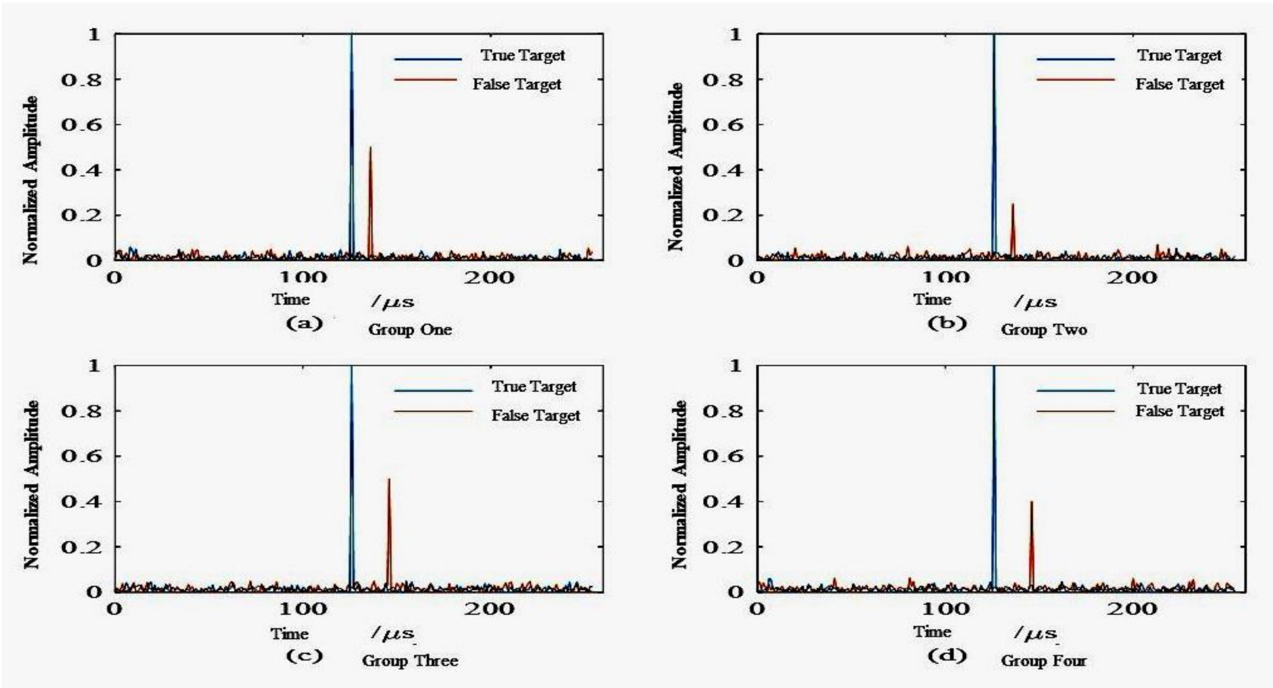

Fig. 2- 3 Matched filtering output of the direct jamming repeater

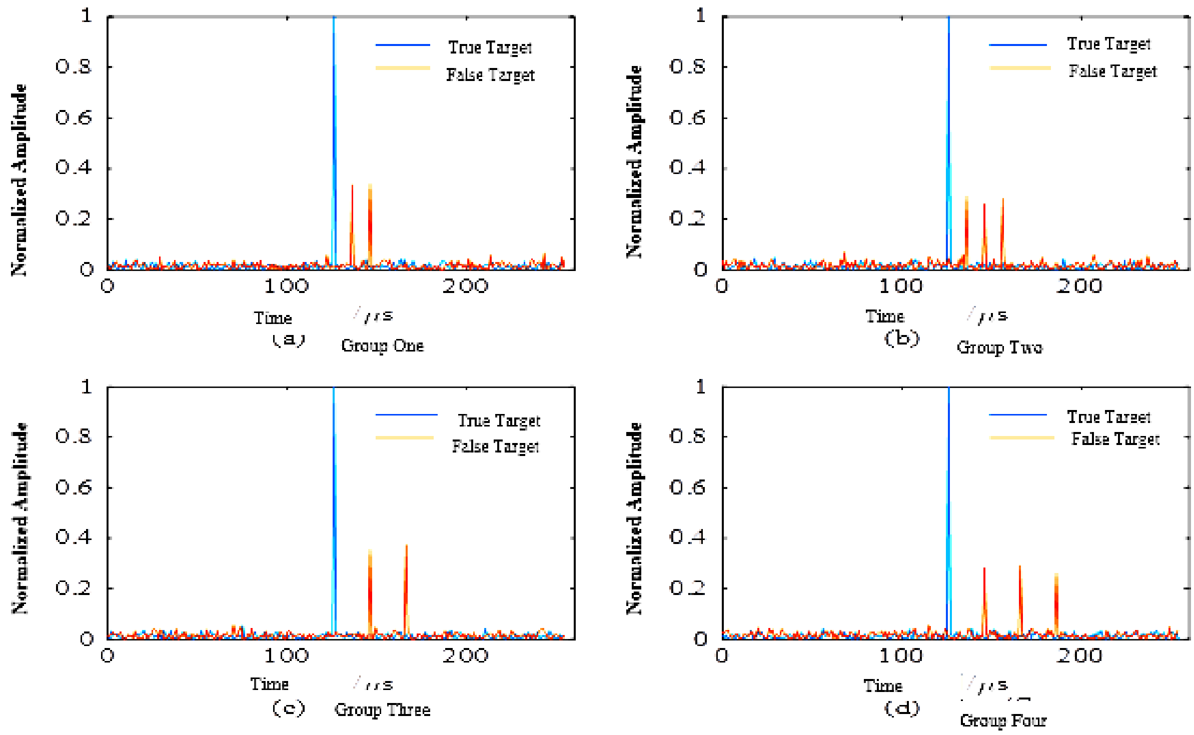

Fig. 4- 1 Matched filtering output of the repeated jamming repeater

As can be seen from Figure 3-4, indirect jamming repeater mode, the amplitude of the false target is related to the duty cycle, and the larger the duty ratio, the greater the amplitude of the false target. However, the jamming equipment can increase the output amplitude of the matched filter of the false target by means of power modulation, making it impossible for the radar to directly identify the jamming signal with energy parameters. At the same time, the delay time of the false target corresponds to the pulse width of the intermittent sampling, and the jamming mode can be recognized by using this information, and then the rough estimation of the jamming power spectrum can be obtained by combining the output amplitude of pulse pressure.

Set multiple groups of the repeated jamming repeater to be in the mode of whole sampling and whole repeating, with specific parameters as follows: ① Intermittent sampling pulse width $\tau=10\mu s$, jamming repetition period $T_s = 30\mu s$; ② $\tau=10\mu s$, $T_s = 40\mu s$; ③ $\tau=20\mu s$, $T_s = 60\mu s$; ④ $\tau=20\mu s$, $T_s = 80\mu s$. The simulation results of normalized pulse pressure output are shown in Figures 3-5.

Compared with Figure 3-4, it can be seen that repeated repeater jamming can increase the number of false targets through multiple slices, but the decline of duty ratio will lead to the decline of pulse pressure output amplitude of false targets, so repeated repeater jamming needs more gain compensation than direct repeater jamming. At the same time, it can be found that the delay time of the false target relative to the true target is also corresponding to the pulse width of the intermittent sampling. After the number of false targets is obtained, the time domain expression of the repeated repeater jamming can be determined by the determination of the delay time.

CONCLUSION

In this research, some problems in the field of CSR anti-active jamming are studied, and some research results are obtained. However, the research content is still not systematic and perfect, and many problems need to be further studied. According to the author's experience in the process of this study, the existing problems and future research directions are summarized as follows:

1. In this research, the ability to identify the active jamming strategy based on matched filtering results is analyzed, so as to provide the estimated value of the jamming signal at the current moment. However, if the forwarding strategy of the repeater jamming signal is changed, the output result of matched filter needs further analysis.
2. To counter the ECM, a phase-coded signal-based CSR has been designed here, which shows excellent results in simulations against jamming. But actual CSR system contains more modulation types, such as linear frequency modulation type. So, the anti-jamming ability of different CSR systems still needs further research.
3.

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