Research on Characteristics and Application of Airborne Nano-Chaff

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Abstract. With the improvement of radar technology, performance of traditional chaff jamming is decreasing constantly. Aiming at the imbalances between the development of chaff jamming and radar technology, a new chaff jamming technology—nano-chaff—is proposed. The basic characteristics of nano-chaff were analyzed before introducing the concept of ideal chaff bomb and studying its scattering characteristics. Simulation results show that, nano-chaff has low radiant efficiency, for which its advantage of loading quantity can make up. Additionally, compared with traditional chaff, it can enhance the RCS of single ideal chaff cartridge. The result can provide some theory basis for applied research subsequently.

1. Introduction
In modern warfare, the ability of electronic countermeasures is the key to determining whether or not to obtain the electromagnetic power successfully. The chaff jamming is a passive electronic countermeasures that combines high efficiency, lightness and low cost[1]. From the time of World War II to the present. The chaff is an essential airborne self-defense equipment necessary for the fighter to perform its mission. In recent years, with the rapid development of electronic technology, the radar and advanced guidance weapon technology has been greatly improved. In the contrast the development of chaff jamming technology is slow, in the game with the development of radar technology. Since the appearance of the chaff, its use methods and specifications have hardly changed. The research on chaff at home and abroad has always stayed in its own characteristics, which has not played a significant role in improving the interference performance. Therefore, in the face of increasingly complex electromagnetic environment and increasingly serious electromagnetic threats, the development of new chaff jamming technology has become inevitable, and nano-chaff is one of them.

The combination of nanotechnology and chaff first appeared in a 2011 news report - Israel uses nanotechnology to create a dandelion-like electronic fiber that can intercept radar-guided surface-to-air missiles. According to reports the mechanism of fiber action is similar to that of traditional chaff, and has superior performance to chaff, such as large carrying capacity, long floating time in the air, and complete invisibility in the air. The description of nano-chaff in China is divided into two types: one is to coat nano-conducting materials on the basis of existing glass fibers, which achieves the effect of widening the scattering band of chaff[2]; another is proposed by Professor Xing Wang of Air Force Engineering University—the half-wavelength chaff with a diameter of nanometers[3]. The research object of this paper is the latter, which will analyze the basic characteristics of nano-chaff in detail,
and compare them with traditional chaffs to reflect their advantages. The research results of this paper can provide theoretical support for experimental research and actual combat in the future.

2. Basic Characteristics Analysis

2.1. Skin depth

Most of the traditional chaffs are made by coating a certain thickness of metal conductive layer on the surface of the glass fiber. The surface conductive layer is subjected to high-frequency electromagnetic waves to generate alternating current, then secondary radiation occurs, in which skin effect is the basic principle. Figure 1 is a basic structural view of a chaff, where \( l \) is the length of chaff, \( r \) is the radius of chaff and \( \delta \) is the skin depth.

Figure 1. Chaff Structure

According to the literature [4], the skin depth can be expressed as

\[
\delta = \frac{1}{k} = \frac{1}{\sqrt{\pi f \mu \sigma}}
\]

In the formula, \( k \) is electromagnetic wave attenuation constant (Np/m), \( f \) is the frequency, \( \mu \) is the magnetic permeability, and \( \sigma \) is the electrical conductivity.

After rough calculation, the skin depths of most good conductor metals are greater than 400 nm irradiated by electromagnetic waves below 18GHz. The nano-chaff involved in this paper have a radius between 10 and 200 nm, so it can be directly considered that the skin depth of the nano-chaff is the chaff radius.

2.2. Half-wave antenna resistance

The energy loss of the dipole antenna is the sum of the heat loss and the radiation loss, that is, the total power consumption of the antenna,

\[
P_a = P_\Omega + P_r
\]

In the formula, \( P_\Omega \) is the heat loss, \( P_r \) is the radiation loss.

So antenna resistance is

\[
R_a = R_\Omega + R_r
\]

In the formula, \( R_\Omega \) is the heat loss resistance, \( R_r \) is the radiation loss resistance.

For a half-wave antenna, all of its radiation resistance is 73.14Ω, so this section will calculate the heat loss resistance of the nano-chaff. According to the literature [5], for conductors with a solid circular cross section, the curvature of the conductor cross section is negligible when the electromagnetic wave frequency is very high, that is to say the cylindrical conductor can be analyzed with the result of the planar conductor. Therefore, a circular-section conductor can be regarded as a planar conductor of infinite depth, and its circumference is the width of the planar conductor. For a circular cross-section half-wavelength chaff with radius \( r \), the heat loss resistance can be expressed as

\[
R_\Omega = \frac{\lambda/2}{\sigma S_c} = \frac{\lambda}{2\sigma [\pi r^2 - \pi (r - \delta)^2]}
\]

For nano-chaff, the above formula can be corrected to

\[
R_\Omega = \frac{\lambda}{2\sigma \pi r^2}
\]

2.3. Radiation efficiency

The radiation efficiency of the antenna is the ratio of the radiated power to the total input power:
Considering that
\[
\left\{ \begin{array}{l}
P_r = \frac{1}{2} I_m R_r \\
P_{\Omega} = \frac{1}{2} I_m R_{\Omega}
\end{array} \right.
\]  
(7)

So radiation efficiency can be expressed as:
\[
\eta = \frac{1}{1 + R_{\Omega} / R_r}
\]  
(8)

Figure 2 depicts the variation of radiation efficiency versus frequency for traditional chaff and nano-chaff. As the frequency increases, the chaff radiation efficiency increases gradually. Nano-chaff with a radius of 120 nm have a radiation efficiency of less than 10% in the frequency range of 2-18 GHz.

3. The RCS of nano-chaff bomb
The RCS of single traditional chaff\(^6\) is
\[
\sigma_s = 0.86 \lambda^2 \cos^4 \theta
\]  
(9)

For nano-chaff, the above formula must be corrected to:
\[
\sigma_s = 0.86 \eta \lambda^2 \cos^4 \theta
\]  
(10)

So
\[
\sigma_s = \frac{125.8 \pi \sigma \lambda^2 r^2 \cos^4 \theta}{146.3 \sigma \pi r^2 + \lambda}
\]  
(11)

When the incident wave polarization is consistent with that of the chaff, the single chaff RCS frequency characteristic curve is shown in Figure 3:
It can be seen from Figure 3 that the single chaff RCS has the same trend with frequency. And the nano type is about three orders of magnitude lower than the traditional type. However, since the volume of the nano-chaff is very small, there is a clear advantage in the number of loading quantity.

In engineering applications, chaff loading quantity is affected by many factors, for example, chaff itself cannot be strictly straight, there must be a gap between the chaffs of the cylindrical section, etc. In view of these factors, the chaff packing density is introduced, which is defined as the ratio of the chaff volume in the unit divided by the total available volume in the unit, typically \([0.2, 0.6]\). The maximum chaff packing density in a chaff bomb can be divided by the cross-sectional area of the chaff of diameter \(d\) divided by the square area of length \(d\):

\[
\rho = \frac{\pi d^2}{d^2} = \frac{\pi}{4} = 0.79
\]  

(12)

Assume that the cross-section diameter \(d' = 5\, \text{cm}\) and length \(l' = 20\, \text{cm}\), the horizontal loadable number of single chaff bomb is:

\[
N_s' = \frac{\pi (d')^2}{\pi (d')^2} = \frac{d^2}{d'^2}
\]  

(13)

The vertical loadable number of single chaff bomb is:

\[
N_v^* = \frac{l'}{l}
\]  

(14)

The ideal loadable number is:

\[
N_s = \rho N_s' N_s^*
\]  

(15)

So the RCS of chaff bomb is:

\[
\bar{\sigma}_j = \eta \eta_s N_s \bar{\sigma}_s
\]  

(16)

\(\eta_s\) is chaff effective coefficient, which indicates that there is adhesion and damage between the chaffs in actual use.

The nano-chaff is 240\,\text{nm} in diameter and the traditional chaff is 30\,\mu\text{m} in diameter. The RCS is analyzed after the chaff bomb is fully dispersed in the air.

It can be seen from Figure 5(a) that although the RCS in the figure shows a decreasing trend with increasing frequency, the rate of decrease is small. It is found by comparing the Figure 5(a) and 5(b) that the effective RCS of the nano-chaff cloud is larger than the traditional type, which exceeds \(4 \times 10^5\, \text{m}^2\) in the range of 2-18GHz, and the effect is very impressive.

![Figure 4](image-url)
4. Application analysis
The laying of the chaff corridor is aimed at shielding the radar target, mainly by utilizing the scattering attenuation effect of the chaff cloud on the electromagnetic wave. The nano-chaff is smaller in weight and lighter than the traditional one, and the falling speed is low. Almost negligible, it can float in the air for a long time, so the use of nano-chaff to covering jamming can play a role in prolonging the duration of jamming. According to Figure 4, in the case where the chaffs are sufficiently scattered, the RCS of nano-chaff cloud is much larger than that of the traditional one. For multiple false targets jamming, the aircraft is often completely concealed in multiple chaff cloud false targets, so the nano-chaff can also be used for dilute jamming and centroid jamming.

In the implementation of centroid jamming, it should be noted that the aircraft should try to place multiple nano-chaff bomb around itself to form false targets. Because its horizontal speed will soon decrease and disappear after being placed, when aircraft flew to the maximum threatening distance of radar tracking mode, it should make a motorized turn and place a chaff bomb at the inflection point to confuse the enemy radar to achieve the best jamming effect.

5. Conclusion
Based on the basic principle of chaff jamming, this paper studies the basic characteristics of half-wave nano-chaff and calculates the RCS of the chaff bomb. The typical tactical application of nano-chaff is explored for the light weight of nano-chaff and the large RCS of chaff scattering. Simulation results show that, nano-chaff has low radiant efficiency, but for the advantage of loading quantity, the RCS of single chaff bomb is much larger than the traditional one. The result of this paper can provide some theory basis for applied research subsequently.

In the next step, the actual diffusion performance of the nano-chaff will be combined to carry out an in-depth study on the air diffusion process of the nano-chaff bomb and the variation of the scattering power.

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