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TOPICAL REVIEW

Chaff Cloud Modeling and Electromagnetic Scattering Properties Estimation

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ABSTRACT Chaff is a radar countermeasure used to interfere with ground radar detection or missile target detection by disrupting the radar. As radar is essential in modern electronic warfare, chaff is also essentially used in many military vehicles. A large amount of chaffs in the form of a thin and long wire is contained in a cylindrical or rectangular cartridge and is launched to form a chaff cloud to disturb the radar. It is virtually impossible to examine the chaff cloud analytically because it is released at once into the air in large quantities. Therefore, for chaff cloud analysis, an approximation method or statistical characteristics are used, or real data is measured directly through experiments. The study of chaff consists of two parts: chaff cloud modeling, which determines the dynamic characteristics of chaff, and estimation of electromagnetic scattering properties, which determines the signal characteristics of the chaff. This review paper focuses on the techniques used in chaff cloud modeling and the estimation of electromagnetic scattering properties. We categorized the techniques by statistical, numerical, and empirical methods. In chaff cloud modeling, studies for the purpose of scattering analysis generally use typical distribution, whereas if chaff cloud modeling itself is the purpose, it is aimed at realizing a realistic chaff cloud by referring to experimental data. For estimation of electromagnetic scattering properties, a conventional method that simply multiplies the average radar cross-section of chaff element to obtain the total radar cross-section of the chaff cloud is used, and a method that allows rapid calculation while considering the distribution of the chaff cloud is being studied.

INDEX TERMS Chaff, chaff cloud modeling, electromagnetic scattering properties estimation, radar cross-section, review.

I. INTRODUCTION

As the introduction of guided weapons has become common in modern weapon systems, it is essential that ships or aircraft have countermeasures against guided weapons. Representative countermeasures include Chaff, Flare, Nixie, and Decoy. Among them, chaff is widely used as the simplest form of radar countermeasure.

The radar determines the distance, direction, and speed of a target based on the return direction and time difference by receiving the reflected wave that returns after radiating the radio wave into the air. The chaff uses this radar principle inversely, diffusing a large number of small metal objects that reflect radio waves very well in the air, forming a radar cross-section (RCS) at the opposite radar larger than the target. Then, the opposite radar can misidentify the chaffs as the target or the radar screen will be full, making it impossible to know the exact location of the target.

Modern chaff puts tens to millions of thin pieces of aluminum or fiberglass coated with metal, such as aluminum, in a cartridge and then launches them as needed. When the chaff has a half-wavelength of the radar wave, the reflection

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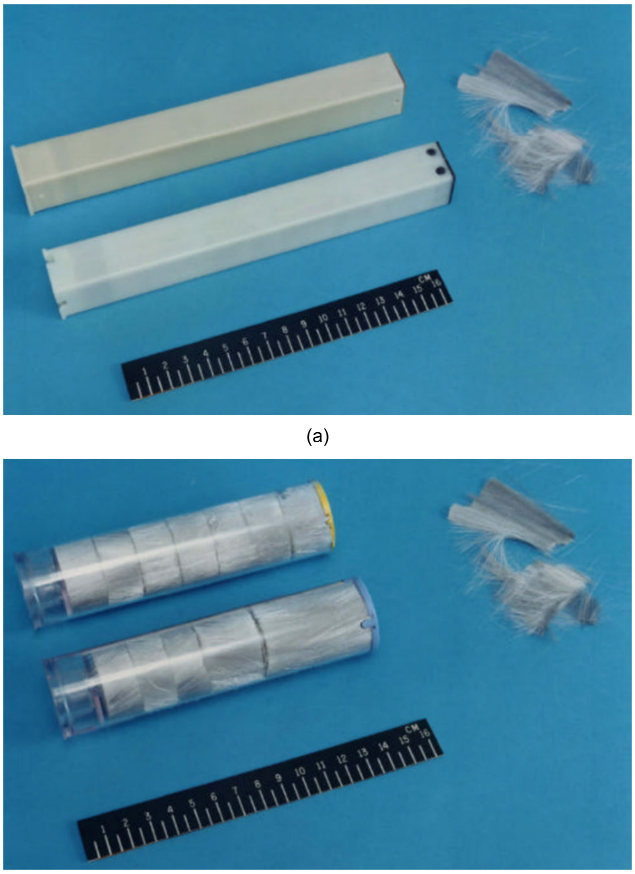

(a)

(b)

FIGURE 1. **Chaff cartridges according to the application (a) RR-188 (top) and RR-180 (bottom) for aircraft use, (b) RR-144 (top) and RR-129 (bottom) for naval use [1].**

effect is maximized. Therefore, chaff with a half-wavelength of the operating frequency of the opposite radar to be disturbed is mainly used. If there is no information on the radar operating frequency, several types of chaff cuts with different lengths are occasionally used by releasing them into the air at the same time.

In addition to aircraft, the chaff is used in most military vehicles such as ships, helicopters, and tanks. The releasing method is usually divided into two types depending on the place of use: aircraft chaff and naval chaff, as shown in Fig. 1. For aircraft chaff, the aircraft directly releases the chaff in the upward or downward direction during flight. In other uses, the chaff is diffused by explosion after launching a chaff bomb. A chaff launch system is essential for naval chaff to counter radar-guided anti-ship missiles. It can also be launched from ground tanks along with smoke grenades to disturb the missiles aimed at the tank, but the duration is very short. Also, intercontinental ballistic missiles generate a chaff cloud during flight to disturb the radar that identifies a warhead, thereby deceiving the opponent. In addition, the periodic release of chaff for distress signals has also been reported.

On the other hand, a technique for distinguishing chaff clouds from a target as a countermeasure against the chaff is also being developed. For example, the target and the chaff cloud are distinguished using the difference in their speed since the aircraft moves at high speed. Technically, features extracted from the range-Doppler image can contain information about speed differences. It also distinguishes the two in that the chaff cloud density decreases over time due to external atmospheric conditions and gravity, but the aircraft remains the same. For another approach, polarimetric decomposition can help recognize the presence of a chaff cloud, as chaff fibers tend to align horizontally as they fall. For these reasons, other decoys have been used, but not all types of radar can distinguish the chaff cloud from the target, and moreover, decoys are generally quite expensive. However, in the case of a ship, it is not easy to distinguish the target from the chaff cloud by radar because the chaff remains in the air for a considerable amount of time when a large amount of chaffs is launched. Although the chaff has disadvantages, it is still widely used in modern military aircraft and ships due to the advantages of low cost and simple operation methods.

Although chaff is still very important as a basic radar countermeasure, analysis and research on chaff are not actively being conducted despite their importance. The difficulties of chaff analysis compared to conventional scatterers are as follows.

- The region of analysis is too large.
- The calculation unit is too large to analyze the characteristics over time.
- There are too many particles.
- Meteorological conditions must be taken into account.
- Matters about chaff are usually confidential and difficult to refer to in experiments.

Research on chaff can be largely divided into chaff cloud modeling and estimation of electromagnetic scattering properties. To analyze the scattering characteristics of a chaff cloud, it is necessary to model how the chaffs are distributed in location or orientation. In previous studies, simple models, such as spheres, ellipsoids, and cuboids, have been mainly used, but though these models are useful for analysis it is difficult to simulate realistic situations. To overcome the limitations of existing studies, recent studies have introduced a dynamic model close to the real environment, with factors such as wind speed, gravity, presence or absence of turbulence, and chaff cartridge launch speed. In addition, based on simulation through a dynamic model, the distribution of the chaff cloud over a certain time is obtained and the scattering characteristics of the chaff cloud are calculated. In this review paper, we discuss the achievements of these studies on chaff cloud modeling, electromagnetic characteristics analysis, and the direction of technological development.

II. MODELING OF CHAFF CLOUD

Geometric modeling of chaff clouds is an essential process for analyzing the effects of electromagnetic interference. This is because the next step, the analysis of characteristics of

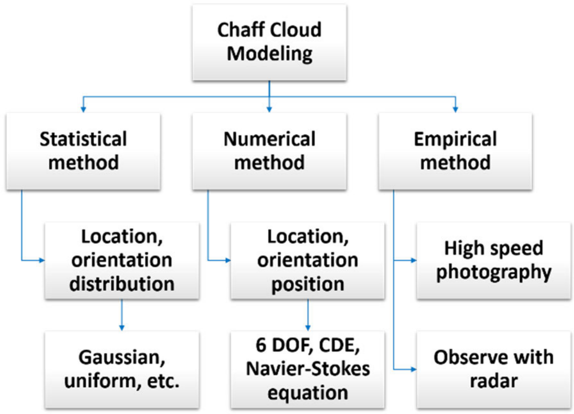

FIGURE 2. Mind map of chaff cloud modeling.

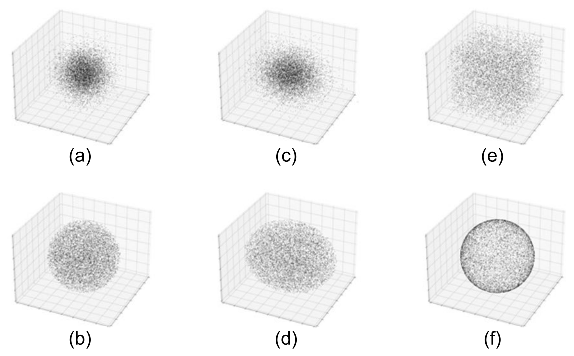

FIGURE 3. Various shapes and distributions of chaff cloud, shape-distribution. (a) Sphere-normal, (b) Sphere-uniform, (c) Spheroid-normal, (d) Spheroid-uniform, (e) Cubic-uniform, (f) Shell-uniform.

very high-frequency signals, is possible only after geometric modeling.

Chaff is usually contained in a chaff cartridge and released into the air. At that time, the movement of the chaff is determined by the aerodynamic characteristics of the chaff or by external factors such as gravity and wind. The movement of the chaff may be modeled by the position, orientation, and speed of the chaff. Methods for modeling in a way as similar as possible to actual chaff clouds are continuously being studied. As shown in Fig. 2, the approach of chaff cloud modeling can be largely categorized into three types: statistical method, numerical method, and experimental method.

A. STATISTICAL METHOD

The statistical method expresses the chaff distribution using statistical models. The chaff can be distributed in a state with random positions and orientations in free space due to external factors such as atmospheric conditions, turbulence, and gravity. Chaff cloud shapes such as spherical [2], [3], spheroid, and cuboid [4] are used to express spherical chaff clouds and chaff corridors. In the case of location distribution, the central coordinates of each chaff are expressed in a uniform or normal distribution in most cases. For orientation distribution, uniform distribution is mainly used. The statistical method has the advantage of being able to simply model a chaff cloud consisting of a large number of chaffs. However, if the probability distribution is not obtained empirically, a difference from the actual chaff cloud may occur. As an example, the orientation distribution of a chaff cloud can be simply determined as a uniform distribution, but the chaff cloud with a practical orientation distribution obtained through experiments may have different polarization characteristics.

Statistical models with typical distributions are mainly used for predicting RCS by applying various electromagnetic analysis techniques to statistically modeled chaff clouds rather than modeling actual chaff clouds statistically. Therefore, in most of the works that focus on the electromagnetic scattering analysis of chaff clouds, they are simply modeled by setting the position and orientation of the chaff cloud as a uniform or Gaussian distribution. Fig. 3 shows chaff clouds of various shapes and distributions.

B. NUMERICAL METHOD

The numerical method mainly handles aerodynamic problems, and it is a method to calculate the dynamic properties of single or multiple chaff using methods such as the convective-diffusion equation (CDE) or six degrees of freedom (6DOF). The numerical method obtains accurate results but has the disadvantage of taking a long time to calculate. Since the number of chaffs used in the real environment reaches millions, modeling a chaff cloud using a numerical method targets a small number of chaffs.

1) 6DOF

6DOF expresses the free movement of a rigid body in a three-dimensional space. The movement is expressed as a combination of free position change on three vertical axes and orientation change through rotation about those axes. That is, 6DOF expresses three-dimensional motion using surge, heave, sway, yaw, pitch, and roll as schematically shown in Fig. 4.

A 6DOF simulation is usually done by first obtaining the aerodynamic properties and then applying them to the 6DOF equation. In [5] and [6], aerodynamic coefficients were obtained through experiments and applied to the 6DOF of chaff, and the simulation results were compared with the experimental results. The details of the experiment are described in the empirical method.

Seo et al. [7] obtained the motion of straight and bent chaffs through the 6DOF motion equation. To obtain the aerodynamic coefficient to be applied to the 6DOF, they estimated the Reynolds number of a slender cylinder chaff and accordingly calculated the aerodynamic force and moment from the aerodynamic module. The Reynolds number is the ratio of forces due to inertia and viscosity, and it quantitatively expresses the relative dynamics of these two types of forces under a given flow condition. Based on the aerodynamic force

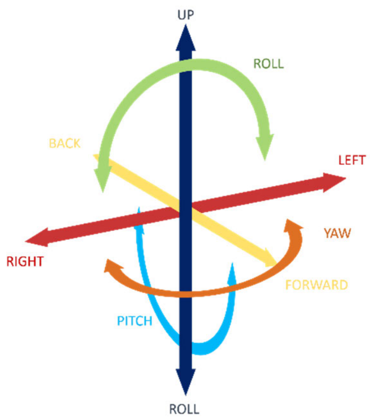

FIGURE 4. Schematic diagram of 6DOF.

and moment, the translational and rotational motion of chaff in 3D is expressed as

$$\begin{aligned}
\sum F_x &= m(\dot{U} + QW - PV) \\
\sum F_y &= m(\dot{V} + RU - PW) \\
\sum F_z &= m(\dot{W} + PV - QU) \\
\sum L &= \dot{P}I_x + QR(I_z - I_y) + I_{xy}(PR - \dot{Q}) \\
\sum M &= \dot{Q}I_y + PR(I_x - I_z) + I_{xy}(QR + \dot{P}) \\
\sum N &= \dot{R}I_z + PR(I_y - I_x) + I_{xy}(Q^2 - R^2),
\end{aligned} \tag{1}$$

where F_x, F_y, and F_z are the force components, and L, M, and N are the aerodynamic moments in the xyz body-fixed coordinate system. U, V, and W are the velocity components, and P, Q, and R are the angular velocity components. I is the moment-of-inertia of the chaff and m is the mass of the chaff.

Figs. 5 (a) and (b) give the shapes of straight and bent chaff clouds after 60 seconds of simulation, respectively. In the figures, straight chaffs and bent chaffs form different shapes of chaff clouds. The straight chaffs are uniformly distributed in the shape of a sphere shell, and the bent chaffs are distributed in the form of a spheroid clustered in the upper center. Since the straight chaffs diffuse while maintaining the initial orientation, it is formed according to the probability distribution of the initially set orientation of the chaffs. In the case of the bent chaffs, even if the initial orientation is different, the more the chaff bends, the faster the posture changes in the direction parallel to the ground. This study on the bent chaff will be useful in that the chaff took a horizontal orientation in several tests and can have longitudinal bending in actual operation.

2) CONVECTION-DIFFUSION EQUATION (CDE)

CDE describes the physical phenomenon in which particles, energy, etc. are transferred inside a system by diffusion and convection. This section describes the application of the CDE to the chaff cloud. In aircraft, chaff operations generally form chaff clouds by spraying chaff in the air. Zuo et al. [8] modeled the physical properties of the chaff and the diffusion process of the chaff cloud by airflow in the situation where the aircraft released the chaffs. Airplanes create wingtip vortexes at the tips of their wings as they fly through the atmosphere. After the chaff is released from the aircraft, it moves under the influence of the vortexes, and to model this situation, the chaff was treated as a gas. Total velocities were obtained by determining the velocity fields generated by both wake vortexes, and the diffusion process by the CDE was modeled as

$$\begin{aligned}
&\frac{\partial\,(x, y, t)}{\partial t} + v_x \frac{\partial s\,(x, y, t)}{\partial x} + v_y \frac{\partial s\,(x, y, t)}{\partial y} \\
&\quad = \xi \left(\frac{\partial^2 s\,(x, y, t)}{\partial x^2} + \frac{\partial^2 s\,(x, y, t)}{\partial y^2} \right),
\end{aligned} \tag{2}$$

where $s(x, y, z)$ is the numerical density, v_x and v_y are velocity components in the x and y directions, and ξ is the diffusion coefficient of the chaff element. In the simulation, the take-off mass of the airplane is 1,500 kg, the wingspan is 40 m, and the flying speed is 450 m/s. The total number of discharged chaffs is 40 million and these elements are released at a flow rate of $10^4/s$.

The diffusion simulation showed that both ends of the chaff cloud were rolled up by the wingtip vortexes over time. Initially, the numerical density of the chaff cloud was not constant, but the numerical density became constant with the flow of air. The chaff cloud modeling using the CDE reflects the wingtip vortexes of a moving aircraft well and is a way to reproduce the real situation. However, this method has a disadvantage in that it is impossible to predict the chaff orientation distribution, which is one of the important parameters for RCS prediction of the chaff cloud.

3) NAVIER-STOKES EQUATION

In this section, we review the modeling of the chaff cloud using the Navier-Stokes equation. The Navier-Stokes equation is derived from Newton's second law and represents the conservation of momentum in a fluid flow. In applying the Navier-Stokes equation to the chaff, several methods of solving a linearized differential equation or calculating the aerodynamic coefficient acting on the chaff using computational fluid dynamics (CFD) are used.

A Stokes flow is a type of fluid flow in which the advective inertial force is small compared to the viscous force, a typical situation when the Reynolds number is very small. At this time, the Navier-Stokes equation can be linearized to become a Stokes equation and can be solved as a linear differential equation. In [9], [10], and [11], the movement of the chaff was modeled based on the Stokes flow model under the assumption that the Reynolds number of the chaff satisfies the condition for linearization. The vertical and horizontal velocities of the chaff obtained by approximating the cylindrical chaff as an elongated spheroid with length l and spheroidal radius c are

$$v = \tilde{v}(\theta)/\mu(z), \tag{3}$$

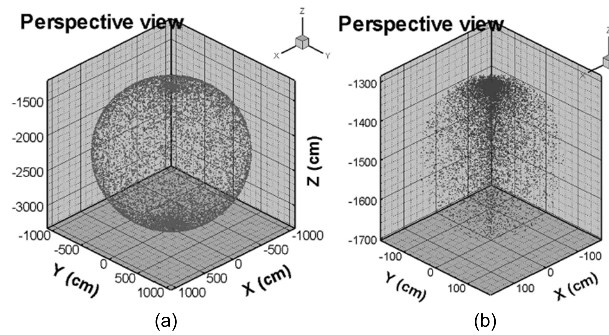

FIGURE 5. Position distribution of chaff after 60 s. (a) Straight, (b) Bent [7].

$$\tilde{v}(\theta) = \frac{g\Delta\rho c^2}{6}\left\{\left[\ln\frac{l}{c} - \frac{3}{2}\right]\sin^2\theta + \left[\ln\frac{l}{c} + \frac{1}{2}\right]\right\}, \quad (4)$$

$$u = \frac{g\Delta\rho c^2}{6\mu(z)}\sin\theta\cos\theta\left[\frac{3}{2} - \ln\frac{l}{c}\right], \quad (5)$$

where v and u are vertical and horizontal velocities, respectively, θ is the elevation angle of the chaff, μ is the atmospheric viscosity with height z, g is the gravitational acceleration, and $\Delta\rho$ is the density difference between the chaff and the air.

As a result of the simulation of the chaff cloud model based on the Stokes equation, the horizontal component RCS was larger than the vertical component RCS, and the intensity of the horizontal component RCS at high altitudes was stronger. These results were obtained according to the experimental result in which the chaff tends to be horizontally oriented, and the horizontally oriented chaff falls more slowly.

The Navier-Stokes equation is commonly solved using numerical methods. Advances in digital computers have revolutionized the solving of aerodynamic problems and have spawned a whole new discipline called CFD. CFD solves and analyzes fluid flow problems using the Navier-Stokes equation applied with numerical analysis techniques and a computer. The closer the model applied to a problem is to reality, the more sophisticated simulation is possible.

In [6], the aerodynamic interference impact factor among the chaffs was calculated to express the movement of the chaff using 6DOF. To determine a turbulence model suitable for calculation, the results of the wind tunnel test were compared with the results of calculating shear stress transport (SST), K-ε, and Reynolds stress turbulence models through CFD. Fig. 6 shows the comparison results.

The selected turbulence model SST served as a computational model of CFD and was used to calculate the effect of the angle of attack, the distance between chaffs, the overlapping area, and the chaff interval on aerodynamic interference to obtain an aerodynamic impact factor. Finally, the aerodynamic coefficient was determined and the kinetic equation of the chaff expressed in 6DOF was determined.

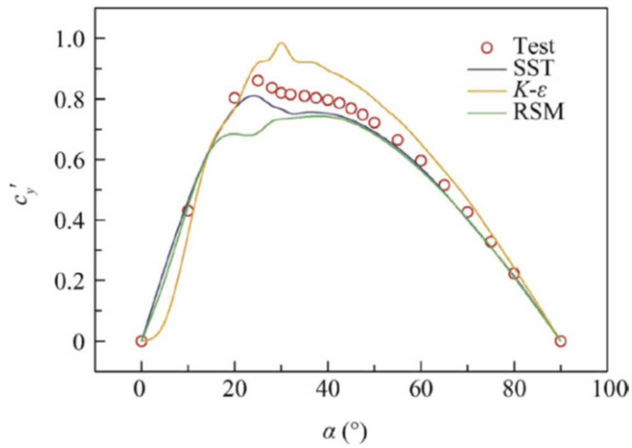

FIGURE 6. Comparison between numerical results and tests at different angles [6].

C. EMPIRICAL METHOD

The empirical method is a method that obtains the diffusion properties of chaff clouds in which complex interactions exist between particles through experiments. The chaff diffusion in the air is affected by a variety of factors, including atmospheric resistance, wind, gravity, and turbulence. Since it is very difficult to accurately model these effects, the method of obtaining the diffusion properties of the chaff cloud through experiments is used. It can be seen that experiments on chaff clouds are often conducted through the observation of echoes caused by chaff clouds on weather radar. However, since most of the research on chaff clouds is for military purposes, the experimental results are rarely made public, so the amount of research literature that is published is very small. For this reason, this section mainly describes the few experiments and the results.

1) TERMINAL FALL VELOCITY

The terminal velocity indicates the final velocity of an object falling through a fluid generating the resistance force can reach. When chaffs are released into the air, they will fall due to gravity. At this time, the chaff that freely falls in the air reaches the terminal velocity, which is a constant velocity at which the falling velocity of the chaff does not change under the influence of drag and buoyancy by air. In 1964, Jiusto and Eadie [12] tested the terminal velocity of chaff in free fall. One type of cylindrical chaff and two types of rectangular chaff were used in the experiment. The terminal fall velocity derived from theoretical approximation and the experimental results in an altitude chamber were compared. The terminal velocity is approximated as

$$V_t \approx [(\pi/21)\,\rho_c g]^{0.73}\, d^{1.19} / \mu^{0.46} \rho_a^{0.27}, \quad (6)$$

where V_t is the terminal velocity, ρ_c is the chaff cylinder density, g is the gravitational acceleration, d is the cylinder diameter, μ is the dynamic viscosity, ρ_a is the air density [12].

The terminal fall velocity using an approximation was calculated for a continuous space of 20 km or less above the Air Research and Development Command (ARDC) atmosphere condition. The chaff drop experiment was performed in an altitude chamber with a height of 2.5 m capable of realizing pressure and temperature at a distance of 20 km. As a result, in the altitude range considered in the experiment, atmospheric pressure, which changes with altitude, rather than air temperature or viscosity, was the dominant variable.

In 2004, Arnott et al. [13] measured the falling velocity by measuring the mass after dropping the chaffs from an 802 cm fall tower. For the measurement and analysis of the falling velocity, the diameter and mass of the chaffs were measured first, and physical properties such as the diameter distribution and the mass and density of the chaff were obtained. Based on these physical properties, theoretical results were derived and compared with the experimental results. The results were consistent with the theoretical results, such that the chaff oriented close to horizontally fell late and the chaff oriented vertically fell faster. However, due to coating imbalance and bird nesting, some chaffs are fell faster than the theoretical result.

2) AERODYNAMIC BEHAVIOR OF CHAFF

The chaff is usually released into the air and falls while interacting with the air in free space. Therefore, in order to know what kind of movement the chaff has in the air, it is first necessary to understand the aerodynamic characteristics of the chaff. In 1975, Brunk et al. [5] performed two experiments. In the first experiment, position and orientation were measured by photographing the chaffs falling in an enclosed test chamber. The second experiment was to see the degree of dispersion by dropping the chaffs and was performed through a drop test in an airship hangar. As results of the experiment, the dynamic behavior of the chaffs was highly dependent on the cross-sectional dimension, and the chaffs showed spiral motion when dropped as shown in Fig. 7. Based on the results, an aerodynamic data package for 6DOF simulation was obtained. The results of the 6DOF simulation showed qualitative agreement with the experimental motion data.

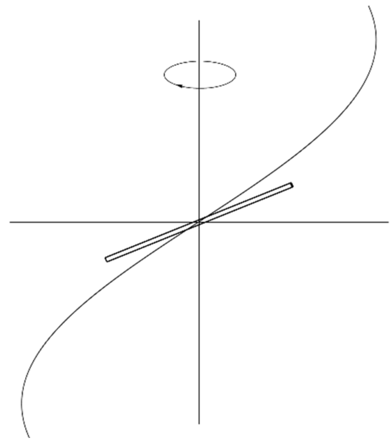

FIGURE 7. Chaff spiral motion.

3) ORIENTATION DISTRIBUTION

One of the ways to distinguish chaff clouds from a target is to use the difference in their polarization characteristics. Due to the elongated wire or rod shape of the chaff, the orientation the chaff takes is closely related to the polarization characteristics. Because of these points, the orientation distribution of the chaff is considered to be an important factor in modeling and estimating the scattering properties of the chaff cloud.

In 1982, Wilkin [14] used four types of typically operated chaff to test RCS polarization characteristics according to the orientation of the chaff. The chaff lengths used in the experiment were 10 mm, 15 mm, 28 mm, and 50 mm, and their target frequencies were 14.3 GHz, 9.5 GHz, 5.1 GHz, and 2.9 GHz, respectively. The experiment was done by dropping the chaffs into a vertical wind tunnel and photographing the chaff through a camera.

To summarize the characteristics obtained from the experimental results, when the chaff is stabilized, it tends to have a horizontal angle. The chaff stabilized quickly after the first few seconds, and showed normal flight motion dominated by angles close to the horizontal. The shorter the length, the closer to the horizontal, and the most common flight motion of the aluminized glass dipoles was within 5 degrees from the horizontal. As time passed after the chaff launch, the orientation distribution gradually approached the horizontal distribution. These results are similar to those of bent chaff in [7].

4) HOLISTIC BEHAVIOR OF CHAFF CLOUD

The holistic kinematic properties of the chaff cloud can be important properties, such as the movement of individual chaffs. Fundamentally, since there is a clear difference between the movement of the chaff cloud and a target, it can be distinguished from the target through the movement characteristics of the chaff cloud itself, and more realistic chaff cloud modeling is possible using the holistic behavior of the chaff cloud.

Huang et al. [6] studied the movement of chaff clouds generated from high-speed objects through wind tunnel tests and experiments using rocket sleds. The experiment was performed to compare with the results of the 6DOF simulation. To this end, the wind tunnel tests were first performed to find a suitable turbulence model. The wind tunnel test is a method to check the interaction of an object with the wind in a large wind-blown tube. The turbulence model selection was made by comparing the wind tunnel test results and simulation results of turbulence models, and the SST turbulence model with the smallest error was selected as the aerodynamic coefficient calculation model.

The experiment was conducted by releasing chaffs covered with pyrophoric material twice into the air while the rocket sled was running on a track, and an infrared thermal imager detected the infrared ray emitted by the ignition of the exposed chaffs to obtain an image of the movement of the chaffs over time. 6DOF simulations were performed assuming an aircraft moving at a speed similar to the rocket sled. Experimental and simulation results are summarized as follows.

- If the distance between the chaffs is greater than 5 times the length of the chaff, the effect of the air projected by the movement of the chaff can be ignored.
- The diffusion shape of the chaff cloud is related to the initial deploying orientation and speed.
- The chaff spreads quickly at first and then becomes almost static.

5) USE OF CHAFF FOR WIND OBSERVATION

In general, in order to reflect radar waves well, the chaff length is a half-wavelength of the opposite radar's operating frequency. Since the chaff reflects radio waves well, it is also used to check the flow of the wind. Smith [15] used chaff to observe winds at high altitudes. The chaff discharge was performed in the range of about 30 km – 90 km, and the result reflected the wind well within the error range.

Dawson [16] collected the results of these experiments and compared them with theoretical equations. The low altitude measurement was compared with the data of [12], and the high altitude measurement was compared with the data of [15]. The result of the comparison revealed that the viscous drag effect is dominant at low altitudes below 50 km, and the free-molecule theory is applied at high altitudes above 75 km. In addition, in the middle slip-flow region, Tsien's equation was confirmed for the cylinder drag. At low altitudes below 50 km, the slowest falling dipoles were the chaff with the smallest mass per unit length, and at high altitudes above 70 km, the terminal velocity was proportional to the density and thickness of the chaff.

In addition, there are many examples of using chaffs for wind observation. In 1999, Lee [17] conducted observations of chaff dropped by airplane using WSR-88D and concluded that chaff can be used as a tool to track the transport and diffusion of air pollutants that diffuse with the wind [18]. The results of these experiments confirm that the chaff is a useful tool to check the wind flow. In other words, the chaff is highly affected by the wind. Therefore, modeling the effect of wind can also be an important factor for the realistic modeling of chaff clouds in battle scenarios.

D. SUMMARY OF METHODS

The methods used for chaff cloud modeling are summarized in Table 1. The empirical method is not included in the table because it obtains several properties directly. The methods were summarized in terms of calculation time, position accuracy, orientation accuracy, and turbulence. The calculation time is an approximate indication of the time required when the method is used. For position and orientation accuracy, the

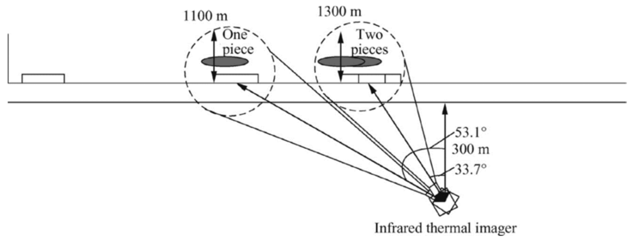

FIGURE 8. Schematic diagram of the rocket sled experiment [6].

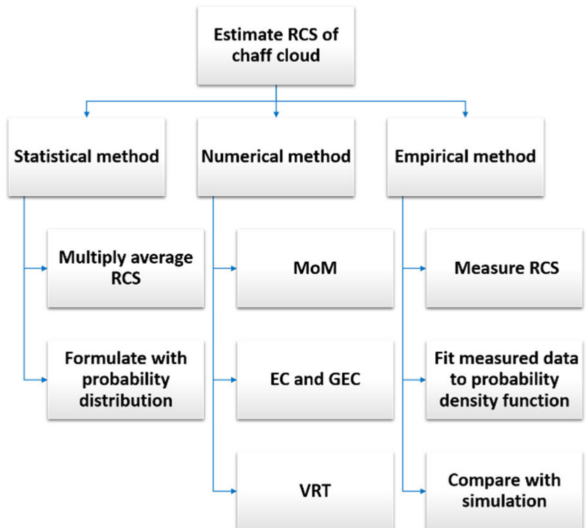

FIGURE 9. Mind map of chaff RCS estimation.

CFD was used as a criterion. Turbulence refers to whether turbulence can be included in the calculation.

III. ESTIMATION OF THE ELECTROMAGNETIC SCATTERING PROPERTIES OF A CHAFF CLOUD

The main purpose of chaff cloud electromagnetic scattering analysis is to enable radar or missiles to distinguish a target from the chaff cloud in order to intercept the target. Characteristics to be analyzed are mainly the RCS by chaff cloud, but additionally, polarization characteristics, Doppler shift frequency, high resolution range profile (HRRP), etc. may be used. As shown in Fig. 9, the method of estimating electromagnetic scattering properties of chaff clouds can be divided into statistical, numerical, and empirical methods similar to chaff cloud modeling.

A. STATISTICAL METHOD

Statistical methods include a method of statistically modeling numerical analysis results or experimental results and a method to obtain the total scattered wave of a chaff cloud by multiplying the average RCS of the single chaff by the number of chaffs. The latter method is simple to calculate but has a disadvantage in that it can be used only when the chaff spacing is wide and has the characteristic of probability distribution because the coupling of chaffs can be ignored

TABLE 1. Summary of modeling methods of chaff cloud.

Category	Methods	Calculation time	Position accuracy	Orientation accuracy	turbulence	REF
Numerical	6DOF	Medium	High	High	○	5, 6, 7
	CDE	Medium	High	Medium	○	8
	Stokes flow	Low	Medium	Medium	X	9, 10, 11
	CFD	High	Criteria	Criteria	○	6
Statistical	Typical PDF	Low	Low	Low	X	2, 3, 4

when the spacing between chaff elements is two or more wavelengths.

Since millions of the chaff are used in actual chaff operations, the method of calculating the average RCS of a single chaff element and multiplying it by the number of chaffs constituting the chaff cloud is most used to calculate the total RCS of the chaff cloud [19], [20], [21], [22]. A slightly different approach is to orient the chaffs to a specific angle and calculate the average RCS [23], [24]. In addition, not only the RCS calculation of the chaff cloud, but also the amplitude and power spectral density (PSD) are expressed through a probability distribution model [25], or the average RCS of the single chaff of various shapes such as round foil and rectangle is obtained [26]. Lim et al. [27] simulated the RCS of single and multiple chaffs according to the length, spacing, tilt angle, and frequency of the chaff.

As above, the statistical method has developed from a method of simply multiplying the average RCS by the total number to a method of obtaining a more precise RCS of the chaff cloud by an adding process.

1) PARTIAL AVERAGE OF CHAFF CLOUD

Since the operation of chaff uses a huge number of chaffs, it is practically impossible to calculate the RCS according to the orientation and position of the chaff in real-time simulation. Considering this problem, Marcus [9] proposed a method to obtain the average RCS by determining N chaffs from the chaff cloud and applied this method to estimate the total RCS considering the beam width of the radar. This is a method of calculating the average of N chaffs in the chaff cloud motion model using the linear Stokes equation and the helical motion model. As N becomes larger, the accuracy increases, but the calculation time also increases.

In [10], two methods were compared and analyzed. The first method calculates the chaff's RCS according to the elevation and azimuth, and the second method calculates the RCS using the method presented in [9]. The total number of chaffs is one million, and as a result of the comparison, the calculation time of the second was very fast, and an error of about 10% was recorded. In the case of $N = 10{,}000$, the calculation times of the first and second methods showed a very large difference with an average of 32.1998 s and 0.2755 s.

2) DCCM

The Discrete Chaff Cloud Model (DCCM) is a method for the electromagnetic modeling of chaff clouds and can evaluate harmonic or wideband impulse scattering responses [28]. This method considers statistical distributions such as chaff density and orientation, and it models various electromagnetic scattering responses of the chaff cloud by one-dimension discretization of the chaff cloud shape into multiple slices. The electromagnetic scattering response can be formulated through the probability density function (PDF) to implement the statistical properties of the chaff cloud according to various situations and conditions. Verification of the DCCM was performed through comparison with the method of moments (MoM) and showed excellent agreement in the time domain and frequency domain.

3) TIME-VARYING RCS OF CHAFF CLOUD

In the early stages of chaff cloud generation, the chaffs are densely packed. Later, the size of the chaff cloud increases due to the effects of explosions, turbulence, and wind. At this time, as the size of the chaff cloud increases, the RCS of the chaff cloud, which was small due to the influence of coupling due to high density and electromagnetic shielding, increases to the maximum RCS that the chaff cloud can generate. Qu [29] expressed the RCS of the chaff cloud as a Rayleigh distribution until and after it is sufficiently diffused. The total RCS of the chaff cloud was obtained by multiplying the average RCS of a single chaff by the number of chaffs. Then it is expressed as

$$\sigma_c(t) = \begin{cases} \eta N \bar{\sigma} \exp(1/2) \frac{t}{d^2} \exp(-\frac{t^2}{2d^2}) & t \leq d \\ \eta N \bar{\sigma} & t > d \end{cases}, \quad (7)$$

where σ_c is the RCS of the chaff, η is the efficiency factor, N is the number of chaffs, $\bar{\sigma}$ is the effective RCS, and d is the parameter of the Rayleigh distribution.

In [30], the RCS of the chaff cloud was expressed according to time as three main phases. The first phase is a blooming phase in which the size and RCS of the chaff cloud rapidly increase, which is modeled as an exponential function. The second is the mature phase in which the size of the chaff cloud is kept and the RCS remains almost unchanged until the decay phase. Finally, in a decay phase, the RCS of the chaff cloud decreases slowly in the early stages and then the decrease speeds up and finally slows down [30].

The signal model of the chaff cloud, which formulates the change of RCS in consideration of time, was used to generate the signal of the chaff cloud in the simulation. Although it has the advantage of quickly obtaining the RCS of the chaff cloud, it has the disadvantage of not being able to obtain a detailed and realistic RCS.

4) POLARIZATION AND RCS

Due to the elongated cylinder shape of the chaff, the polarization of the electromagnetic wave depends on the orientation of the chaff. Moreover, since the chaff cloud consists of a large number of chaffs, it generally has a certain statistical characteristic when viewed from a statistical point of view. In [31], the average RCS was calculated by considering the linearly polarized vertical, horizontal, and circularly polarized left-handed and right-handed radar systems and the resulting chaff polarization.

Tang et al. [32] distinguished targets and a chaff cloud by the PDF difference of the polarization-RCS ratio. The polarization-RCS ratio refers to the ratio of RCS according to the polarization of the incident wave and the scattered wave. In the process of obtaining the polarization-RCS ratio through the probability distribution, the MoM's formula was used to simplify the derivation of the formula. Based on this, PDFs were obtained in the case of uniform orientation distribution, vertical polarization, and horizontal polarization.

B. NUMERICAL METHOD

Methods for numerically analyzing the chaff cloud include the MoM, one of the low-frequency techniques, the equivalent conductor (EC), and the generalized equivalent conductor (GEC) method, which equalizes the entire chaff cloud as a continuum. In addition, the vector radiative transfer (VRT) theory has been applied to calculate the RCS of a chaff cloud. This section reviews the methods mentioned above.

1) METHOD OF MOMENTS

The MoM, a low-frequency analysis technique, can apply to not only plane meshes but also wire meshes, thus it is quite effective to calculate the scattered field from wire-type scatterers like chaff. Moreover, it has the advantage of being able to analyze cases where the analysis area is not limited and infinite. The MoM also has the advantage of being able to calculate the coupling between chaff elements, but due to the disadvantage that only a small number of chaffs can be analyzed because of the problem of computational amount, it is practically impossible to analyze the chaff cloud using the MoM. In [33], the chaff cloud was analyzed by considering the coupling between chaffs using the MoM, but the maximum number of chaffs was only 200. A software tool such as HFSS was used to analyze the chaff clouds, but the maximum number was 2,000 [34]. Another use of the MoM is to validate the results of the analysis of chaff clouds with the method that proposed by the authors. In [32] and [35], the electromagnetic properties of the chaff cloud were analyzed through the proposed method and these results were compared with the analysis result by the MoM to verify the effectiveness of the method. As such, the MoM has become increasingly used as a verification tool in one analysis tool.

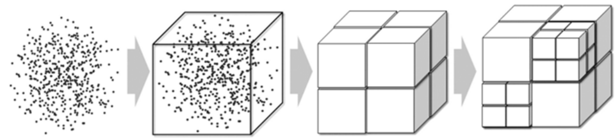

FIGURE 10. Recursive subdivision of chaff cloud into eight sub-blocks [7].

2) EQUIVALENT CONDUCTOR AND GENERALIZED EQUIVALENT CONDUCTOR METHOD

The EC method was proposed by Marcus [36], [37], [38], and [39] as a method of calculating the RCS with the chaff cloud as an equivalent effective medium. In this method, it is assumed that randomly oriented dipoles are randomly distributed in a space of a certain thickness. This infinite slab is regarded as a continuous conductor instead of the chaff cloud, and the RCS is calculated to obtain the RCS of the chaff cloud. The method showed good agreement in comparison with the results of the MoM.

However, in the actual chaff cloud, the density and orientation of the chaff are not constant. Seo et al. [7] developed the EC method to be able to calculate the total RCS of the chaff cloud considering the density of the chaff cloud and the distribution of the orientation of the chaff. Furthermore, he divided the chaff cloud into multiple sub-blocks and calculated the RCS of each sub-block using the GEC. The sub-blocks are divided by the octree algorithm so that the number of chaffs is less than 1,000 as in the process shown in Fig. 10. Each sub-block has the same or a different density level and orientation distribution, and accordingly, the GEC method can be applied to obtain the RCS. The GEC method enables rapid analysis of large and high-density chaff clouds, which are difficult to calculate with the finite-difference time-domain (FDTD) or MoM. The simulation results of chaff clouds with straight and bent chaffs by the GEC and MoM, respectively, and their comparison is shown in Figs. 11 (a) and (b).

3) VECTOR RADIATIVE TRANSFER METHOD

With the MoM, it is almost impossible to handle a high-density chaff cloud composed of a large amount of chaff, whereas the VRT theory handles transfer in a medium in which randomly distributed particles exist. The VRT obtains

TABLE 2. Summary of electromagnetic scattering properties estimation of chaff cloud.

Category	Methods	Calculation time	Accuracy	Coupling between chaffs	Various chaff cloud shape	Chaff orientation	REF
numerical	MoM	Very high	Criteria	○	○	○	7, 32, 33, 34, 35, 36, 37, 38, 39
	EC	Medium	Medium	△	X	X	36, 37, 38, 39
	GEC	Medium	Medium	△	X	○	7
	VRT	Medium	Medium	△	○	○	8, 40, 41
statistical	Multiply average RCS	Low	Low	X	X	X	19, 20, 21, 22, 23, 24, 25, 26, 27
	DCCM	Medium	Medium	X	○	○	28
	Partial average	Low	Low	X	X	△	9, 10

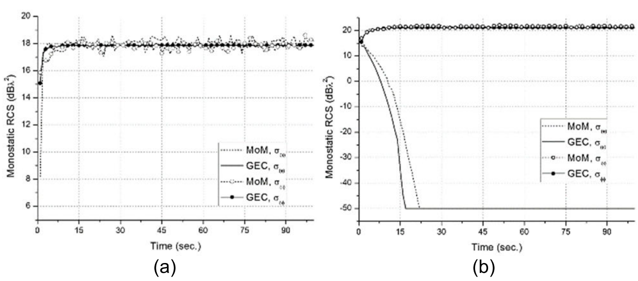

FIGURE 11. Comparison of monostatic RCS by MoM and GEC method for chaff cloud of one thousand. (a) Straight fibers. (b) Bent fibers [7].

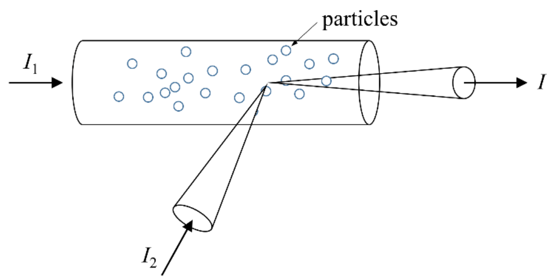

FIGURE 12. Schematic diagram of VRT.

a specific intensity change through the medium, including both the scattering and absorption of particles, the emission, and the effects of other sources. It has been studied recently and can overcome the disadvantage of statistical methods that cannot consider coupling and the inability to calculate a large amount of chaff, which is considered a disadvantage of numerical methods such as MoM and FDTD. Fig. 12 shows how the specific intensity passes through the space where the particles are distributed.

In [40], the VRT was introduced as a method for analyzing high-density chaff clouds composed of a large amount of chaff. The simulation with the VRT uses the Monte Carlo method and analyzes chaff clouds with a radius of 4 m, consisting of 30,000 and 500,000, respectively. Li et al. [41] analyzed a chaff cloud with 5 million chaffs with a 7 m radius with three distributions: uniform distribution, dense in the middle, and sparse in the middle. Their study showed that the VRT method is sufficiently capable of calculating high-density chaff clouds. Zuo et al. [8] compared VRT, commercial software, and indoor measurement. As a result of the comparison, a calculation error of up to 10% was obtained with commercial software simulation, and a calculation error of up to 15% was obtained with the result of indoor chaff cloud model measurement.

C. EMPIRICAL METHOD

Experimenting on the scattering properties of the chaff cloud is an important method that can consider all the complex factors that theoretical calculations cannot take into account by directly measuring the chaff cloud. A few experiments related to the chaff cloud have been reported, but since the operation of the chaff is mainly for military purposes, analysis of the measured results is rarely disclosed. In general, the use of measured results is for verification and comparison of methods proposed in the literature, but since data is obtained from direct measurement, the measurement results are also modeled as a probability distribution model.

In [42], the scattering characteristic data of the chaff cloud measured in X-Band and S-Band were defined as a probability distribution model, and goodness of fit was verified

TABLE 3. Summary of studies on chaff.

REF	Situation	Modeling method	Signal analysis method	Software tool	Characteristics
[1]	Unspecific	-	-	-	1. A study on the impact of chaff on the environment and humans.
[2]	Naval	Statistical	Statistical	MATLAB	1. Parameterized chaff model. 2. Chaff cloud model for scattering properties.
[3]	Naval	Statistical	Polarization characteristics	CST	1. Polarization information is used. 2. Distinguishable when the echo of the chaff and the ship does not overlap.
[4]	Aircraft	Statistical	Empirical	-	1. Indoor measurement of elliptical and cubic chaff clouds and small
					target model.
[5]	Unspecific	Empirical	-	-	1. The chaff used in the experiment was selected from four basic types of chaff.
[6]	Aircraft	Empirical, CFD, 6DOF	-	STAR-CCM+, MATLAB	1. Comparison of wind tunnel test results and numerical results. 2. The chaff coated with pyrophoric-activated metal magnesium was photographed using an infrared thermal imager.
[7]	Unspecific	6DOF	GEC	-	1. Simulation of straight and bent chaff. 2. The local density of the chaff cloud is considered.
[8]	Aircraft	CDE	VRT	-	1. Two types of chaff cloud models. 2. EM transmission properties were obtained using MoM. 3. Airflow is considered.
[9]	Aircraft	Stokes flow model	Partial average	-	1. Chaff cloud with a small Reynolds number. 2. A model considering the observation results of the chaff cloud.
[10]	Aircraft	Stokes flow model	Partial average	FEKO 7.0, MATLAB	1. Comparison of two RCS prediction methods. 2. Configures the RCS of the chaff cloud as a look-up table.
[11]	Aircraft	Stokes flow model	Polarization characteristics	MATLAB	1. Three typical chaff distributions.
[12]	Aircraft	Empirical	-	-	1. Cylindrical and rectangular chaffs were used in the experiment. 2. Altitude chamber in non-turbulent condition for heights of 20 km or less.
[13]	Unspecific	Empirical	-		1. The diameter distribution of the manufactured chaff is considered.
[14]	Unspecific	Empirical	-		1. Orientation distribution of chaffs of 4 different lengths. 2. The free fall of the chaff is realized by blowing the wind upwards according to the falling speed.
[15]	Unspecific	Empirical	-		1. A 2-inch long chaff was used for wind observation purposes.
[16]	Unspecific	Empirical	-		1. Comparison of chaff's theory of falling velocity and experimental results. 2. Heights up to 100 km are considered.
[17]	Aircraft	Empirical	-		1. Comparison of the theoretical and observed diffusion coefficient. 2. Observation with WSR-88D Radar.

TABLE 3. ***(Continued.)*** **Summary of studies on chaff.**

[18]	Aircraft	Empirical	-		1. Comparison of the theoretical and observed diffusion coefficient. 2. Observation with WSR-88D Radar.
[19]	Unspecific	Statistical	Statistical	MATLAB	1. A study on the existence of two or more chaff clouds. 2. Analysis of two lengths of chaff.
[20]	Naval and avionic	-	Statistical		1. The chaff, emitter, and environment are parameterized to model the scattering properties.
[21]	Unspecific	Statistical	Statistical	MATLAB	1. A study on target tracking in a cluttered environment.
[22]	Chaff bomb	Stokes flow model	Statistical		1. The process of chaff cloud diffusion is modeled separately.
[23]	Unspecific	Statistical	Statistical		1. Non-coherent experimental data were used.
[24]	Naval	Statistical	Statistical	SILEM	1. About SILEM software.
[25]	Unspecific	Statistical	Statistical		1. A model of the scattering properties of a chaff cloud.
[26]	Unspecific	Statistical	Statistical		1. A model of the scattering properties of a chaff cloud.
[27]	Aircraft	Statistical	Statistical		1. Analysis of three different lengths of chaff.
[28]	Unspecific	Statistical	Statistical		1. Electromagnetic model considering the geometry and statistical distribution of the chaff cloud.
[29]	Aircraft	Statistical	Statistical		1. The chaff spreading time is taken into account.
[30]	Chaff bomb	Statistical	Statistical		1. The process of chaff cloud diffusion is modeled separately. 2. The scattering properties of a chaff cloud are modeled.
[31]	Unspecific	-	Statistical	-	1. The average RCS of a single chaff is calculated according to different polarizations.
[32]	Aircraft	Statistical	Statistical	Compaq Visual Fortran software	1. A study to distinguish between target and chaff by the ratio of polarization.
[33]	Unspecific	Statistical	MoM		1. A study of dense chaff clouds. 2. The polarization of the RCS is taken into account.
[34]	Unspecific	Statistical	FEM	HFSS	1. Analysis of four different lengths of chaff.
[35]	Unspecific	Statistical	Statistical	NEC	1. Bistatic RCS. 2. Method based on uniform distribution of sphere shape.
[36]	Unspecific	Statistical	EC	NEC	1. Coupling, shielding, and high density are considered.
[37]	Unspecific	Statistical	EC	NEC	1. Thickness is considered.
[38]	Unspecific	Statistical	EC	NEC	1. Coupling, shielding, and high density are considered.
[39]	Unspecific	Statistical	EC	NEC	1. Incoherent scattering is the focus.
[40]	Unspecific	Statistical	VRT		1. Method for evenly distributed and oriented chaffs.
[41]	Unspecific	Statistical	VRT		1. Three cases of distribution are considered.
[42]	Chaff bomb	-	Empirical		1. PDF of RCS was modeled with RCS measurement data.
[43]	Unspecific	Statistical	Empirical	MATLAB	1. Indoor measurement 2. A theoretical model was created before the physical model was built.
[44]	Unspecific	-	Empirical		1. Indoor measurement
[45]	Unspecific	-	Empirical		1. Indoor measurement 2. Four frequency bands are considered.

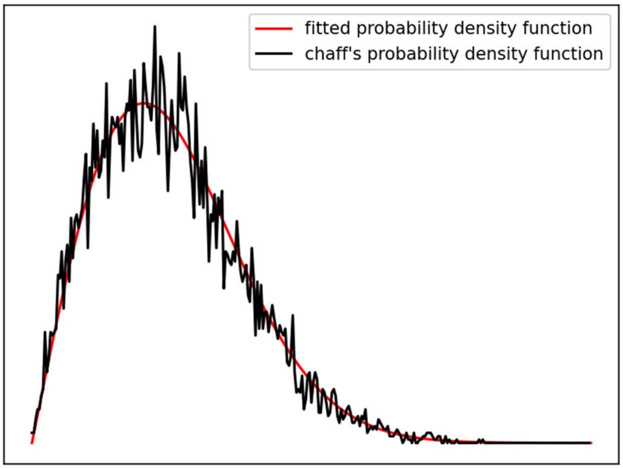

FIGURE 13. Example of fitting chaff's probability density function.

through verification. Fig. 13 is an example of a fitted probability distribution model of chaff cloud data. The red line is the fitted PDF and the black line is an example of the PDF of the measured chaff data.

In some papers, experiments were performed by directly making a physical model of the chaff cloud. Xidian University is equipped with facilities to create physical models of chaff clouds [43] and to measure chaff cloud models indoors [44]. The physical model of the chaff cloud is made of polystyrene so that the reflection of the object used to hold the chaff is negligible. By adjusting and fixing the position and orientation of each chaff on polystyrene, It is possible to implement a model of a chaff cloud with information of position and orientation distribution. The experimental method implements a physical model of the chaff cloud and measures it in an indoor measurement facility. The obtained results are compared with the simulation results of the methods proposed in the literature as follows. Various studies have been conducted, such as comparing the two chaff cloud models with commercial software and VRT methods [8], measuring the range profile of elliptical and cubic chaff clouds and comparing the four classification methods [4], and testing the jamming performance for wideband jamming of the newly designed chaff [45].

D. SUMMARY OF METHODS

Among the reviewed papers, the methods used for estimation of electromagnetic scattering properties are summarized in Table 2. For the same reasons as in Section II, empirical methods are not included. Methods are expressed as items of calculation time, accuracy, coupling between chaffs, various chaff cloud shapes, and chaff orientation. Calculation time refers to the time required to calculate the RCS of the chaff cloud. Accuracy roughly indicates how accurate results are obtained compared to the MoM. Coupling between chaffs indicates whether coupling between chaffs is considered, and various chaff cloud shapes indicate whether various shapes of chaff clouds can be calculated. Chaff orientation indicates whether chaff orientation is taken into account.

Table 3 summarizes the papers reviewed in this paper by the situation, modeling method, electromagnetic scattering properties estimation method, software tool, and features. The modeling and electromagnetic scattering properties estimation method items represent the methods used among the statistical, numerical, and empirical methods categorized in this review paper. A software tool is a tool used somehow in the paper, and the characteristic is a brief summary of the special point of the paper.

IV. CONCLUSION

Chaff is generally a metal-coated fiber. As a radar countermeasure that interferes with radar detection in a way that generates a large RCS, it is an important and basic piece of equipment that is used in most military vehicles such as aircraft and ships. As a countermeasure against chaff, technology for distinguishing a chaff cloud from a target is being developed. In this paper, we reviewed relatively recent papers on the subject. We focused on the method of modeling the chaff cloud and the method of estimating the electromagnetic scattering properties of the chaff cloud and we categorized them according to our proposed criteria. We tabulated the techniques used for modeling and estimating the electromagnetic scattering properties of the chaff cloud with respect to performance-related factors.

Chaff cloud modeling is an essential process for estimating electromagnetic scattering properties. It mainly models the physical movement of the chaff and the resulting position, orientation, and velocity. In this paper, we categorized modeling methods into three categories: statistical methods, numerical methods, and empirical methods. The chaff cloud has occasionally been expressed as typical probability distribution models such as Gaussian and uniform, but those studies focused on the method of scattering analysis of chaff clouds. Realistic chaff cloud modeling was made by realizing the aerodynamic movement or position and orientation distribution of chaff in the air by referring to the results of the experiment on chaff.

The aim of estimating the electromagnetic scattering properties of the chaff cloud is to make it possible to distinguish a target from the chaff cloud, and RCS analysis is the main tool. We made three categories of the analysis methods for scattering characteristics: statistical methods, numerical analysis methods, and empirical methods like modeling. For scattering analysis of chaff clouds, the average RCS of single chaff was obtained, or precise RCS was computed using the MoM. Recently, the MoM, which is considered the most accurate method, has also been used to verify the validity of the methods proposed in the literature. In addition, the estimation of electromagnetic scattering properties has evolved from simply multiplying the average of the single chaff's RCS by the number of chaffs to a method that can obtain or simulate the characteristics of a practical signal by calculating a large number of chaffs while reflecting the location and orientation distribution of chaff clouds.

In the not-too-distant past, battle scenario simulations were performed simply by multiplying the average RCS of single chaff by the total number of chaffs to obtain the RCS of the chaff cloud. However, now the aim is to realize a more realistic chaff cloud by improving computing power and accumulating experimental results. Our group is going to simulate the chaff dynamics using the computational fluid dynamics / discrete element method model and estimate the dynamic RCS of the chaff cloud using the VRT and GEC methods. Ongoing research will enable real-time battle scenario simulations, and these advances will increase the accuracy of target detection.

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