Visualization of Chaff Cloud Aerodynamics based on Random Generation of Chaff Dipoles in 3D Space

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Abstract: Chaff is one of the most widely used and effective expendable electronic attack (EA) devices. It is a form of volumetric radar clutter consisting of multiple metalized radar reflectors known as chaff fibers designed to confuse hostile radar operation. It is dispensed into the atmosphere to deny radar acquisition, generate false targets. To understand the dynamics of chaff cloud, a software has been developed by introducing a methodology which takes concern of various dynamic parameters like ejection velocity, blooming and settling, and terminal velocity of chaff fiber. The software is developed in a high level programming language, known as MATLAB [1]. The chaff fibers were generated randomly in 3D space at t=T0, i.e. ejection. Then the blooming code was implemented on these randomly distributed fibers to visualize the entire 3D chaff cloud at any given time (t). Output of the software is in the form of images and video which show the complete evolution of chaff cloud and its final settling. In images as output, the chaff fiber distribution in 3D space was shown on different time. In video as output, all the images were taken in sequence in MATLAB and the complete blooming is visualized. This software finds its main application in evaluating the dynamic RCS behaviour of chaff cloud.

I. INTRODUCTION:
In war scenario, once a missile seeker has locked on to a target the seeker continues to track the target by centering its resolution cell over the centroid of the radar returns. The locked target, using an onboard electronic counter measure dispensing system (CMDS) fires few chaff cartridges having chaff payload consisting of a large numbers (few millions) of dipoles cut to different resonant lengths to cover broad frequency range (2-18GHz). Under the influence of kinetic energy imparted by impulse squib inside the cartridge and wake factor due to aircraft velocity a rapid blooming of chaff cloud takes. With the result within in few milliseconds of firing the cartridges, a chaff cloud of sufficient size is formed close to the aircraft within the view of the missile’s seeker range cell. As the cloud generates the strong radar return the missile homes on to the cloud in preference to the aircraft. Depending on the aircraft maneuverability, the two diverge with the result de-locking takes place and missile is diverted away from its true target [2, 3].

The rate at which chaff will scatter is called as Bloom Rate. The ability of chaff to effectively defeat a target tracking radar is directly related to the chaff dispense rate, which determines the chaff RCS, which should be larger than the aircraft’s RCS. RCS is a measure of the net reradiated energy from a target to the illuminating radar. Formal definition of Radar Cross Section:

\[ \sigma = \lim_{R \to \infty} 4\pi R^2 \frac{|E_s|^2}{|E_0|^2} \quad \ldots (1) \]

Where, E0 is the electric-field strength of the incident wave striking on the target, Es is the electric-field strength of the scattered wave at the radar and R is Radius.

The RCS of an aircraft varies based on the size, shape, type of skin surface, configuration, and aspect to the illuminating radar. To understand the chaff cloud functionality, it is important to analyse its blooming behaviour. Chaff bloom rate is dependent on aerodynamic factors associated with the chaff type, the location of the dispenser on the aircraft, and the aircraft wake or turbulence. Heavy or dense chaff falls
faster and blooms slower than lighter and less dense chaff. In the present studies, air turbulence factor is not taken into consideration.

II. 3D CHAFF CLOUD BLOOMING MODEL

Figure 1 shows the various velocity components acting on a single Chaff fiber.

![Figure 1: Showing the V_x, V_y, and V_z Components](image)

Here $\theta$ and $\Phi$ are the angle between the dipole and the velocity component. The blooming of the chaff cloud will depend upon the ejection velocity ($V_e$) which is determined by the internal pressure generated on the chaff fibers. The vertical and horizontal components of velocity will be as follows

$$V_x = V_e \cos (\theta) \cos (\Phi) \quad \text{(2)}$$
$$V_y = V_e \cos (\Phi) \sin (\theta) \quad \text{(3)}$$
$$V_z = V_e \sin (\Phi) \quad \text{(4)}$$

Here, $V_x$ and $V_y$ are along horizontal component, $V_z$ is along vertical component, $V_e$ is for ejection velocity.

III. METHODOLOGY:

Chaff consists of millions of Dipoles. In order to form chaff cloud it is necessary to draw the dipoles on the screen. Dipoles is represented or symbolized by the ‘line’. The distance formula stated below as equation (5) is used to find out the length of the dipole. The lengths of all the dipoles are same for the specified frequency.

Thus the problem of Dipole-Generation can be considered as creating ‘n’ number of dipoles (i.e. line segments) of particular (fixed) lengths constrained within a sphere (circle for 2D) of a specific radius. Thus, in order to approach for a solution of this problem, parametric co-ordinates were taken handy. As a pre-requisite, for a sphere of radius ‘r’ any point lying on the sphere surface can be written as:

$$\{x, y, z\} = \{x_0 + r \cos (\theta) \sin (\phi), y_0 + r \sin (\theta) \sin (\phi), z_0 + r \cos (\phi)\} \quad \text{(5)}$$

where,
- $r$ = Radius of Sphere;
- $\theta$ = angle made by $r$ vector with positive Z axis
- $\phi$ = angle made by projection of $r$ vector on the XY plane with positive X axis
- $\{x_0, y_0, z_0\}$ = co-ordinates of the center of sphere

Further for any point lying inside the volume of sphere, the co-ordinates can be modified to:

$$\{x, y, z\} = \{x_0 + R \cos (\theta) \sin (\phi), y_0 + R \sin (\theta) \sin (\phi), z_0 + R \cos (\phi)\} \quad \text{(6)}$$

where $R = r \cos (\theta)$

As modulo cosine function restrains itself within [0 1] this gives us surfaces of all the spherical shells within the sphere thus constituting the any point in sphere volume of radius ‘r’.

Now in order to construct randomly aligned dipoles of fixed length, we can consider the random points generated before as the midpoints of the dipole. Now an imaginary sphere can be imagined with the point as the centre and diameter as the dipole length. Any random point can be picked from this spherical shell and another just diametrically opposite to it using the mid-point formula.

Thus a line can be plot using the parametric equations of a line between two points in 3D space.

$$x = (x_2 - x_1) t + x_1 \quad \text{......(7)}$$
$$y = (y_2 - y_1) t + y_1 \quad \text{......(8)}$$
$$z = (z_2 - z_1) t + z_1 \quad \text{......(9)}$$

Where,
\{x, y, z\} - are the co-ordinates of any point lying on line segment b/w \{x_1, y_1, z_1\} and \{x_2, y_2, z_2\}

Thus randomly generated dipole at t=0sec will bloom under the influence of ejection velocity, atmospheric factor etc. By improving blooming equation (2, 3, 4) the chaff cloud blooming can be initialized at any time t.

After the generation of dipoles, Visualization of blooming and settling of cloud is to be carried out. Ejection Velocity will be responsible for the blooming of the cloud and is taken as the input from the user and terminal velocity will be responsible for the settling of the cloud and the formula is[5):

\[ V = \frac{g \Delta \rho \pi c^2}{6 \mu} \left[ \ln \left( \frac{2}{3} \right) \sin^2 \theta + \left( \ln \left( \frac{2}{3} \right) + \frac{3}{2} \right) \right] \ldots \ldots (10) \]

Where
- \( \mu \) = viscosity of the fluid
- \( = 1.983 \times 10^{-5} \text{Kg/m.s} \) for air
- \( v \) = Terminal velocity m/s
- \( l \) = length of fiber
- \( c \) = radius of fiber
- \( g \) = gravitation acceleration
- \( \Delta \rho \) = density difference between fiber and air

new_coordinates(i,10) will be the orientation angle values of the dipoles.

With the effect of time the coordinates i.e. the positions of the dipoles will change. New coordinates of the dipoles will be calculated by using the given expressions:

\[ X = \text{Initial} + \left( \frac{v_h}{p} \right) \times (1 - e^{-pt}) \ldots \ldots (11) \]
\[ Y = \text{Initial} + \left( \frac{v_h}{p} \right) \times (1 - e^{-pt}) \ldots \ldots (12) \]
\[ z = \text{Initial} + \left( \frac{g}{p} \right) \times (1 - e^{-pt}) - (v_T \times \text{time}) \ldots \ldots (13) \]

In 3D, the falling of dipoles will be along Z-axis. In real scenario, the cloud will start blooming with some ejection velocity. After some time ejection velocity will become zero and the cloud will start falling with some terminal velocity. Similar method can be applied in 2D for generating the dipoles and visualization of cloud with the consideration just Y-axis also.

III. RCS Behaviour with respect to aspect angle

The backscattering from the dipole is given by the expression,
When \( \theta_t = \theta_d \), then it the expression of mono static RCS \( \varphi_l \) and \( \varphi_d \) are the angles depending upon the polarization condition on transmission and reception.

\[ \varphi_l = \varphi_d \] for co-polar measurement & \( \varphi_l = 90^\circ \pm \varphi_d \) for cross polar measurement

Thus the equation can be simplified to,

\[ \sigma(\theta_t, \varphi_l, \theta_d, \varphi_d) = \sum_{i=1}^{n} \frac{2}{\pi} \lambda^2 \cos^4 \phi_i \ldots (15) \]

IV. RESULT:

Chaff cloud blooming of 1 lakhs element is simulated by in house developed software. Figure below show the blooming behaviour at different time period.
V. Conclusion:

The problem is to apply a certain dynamic conditions upon each randomly generated cum oriented chaff fiber, to present the current situation of the fibers (using different colours for different lengths) as a 3 dimensional plot and further display these plots in form of visual blooming in real time.

The dynamic factors are computed and stored per-requisite in order to provide direct accessing and zero duplicate value generation time loss. Rest the values are computed as per the equations and new co-ordinates are assigned and chaff is plotted. These plots are stored as images (JPEG) and later displayed one after another with a certain time lag. In this way 3D visualization of chaff cloud as video output is analyzed. Its RCS variation with respect to aspect angel is also analyzed.

VI. Reference:


Similarly, one can analyze the blooming at any given time and based on configuration of dipole RCS v/s aspect angle can be evaluated. By cascading these images blooming wrt time can be visualized in video format.