

RESEARCH ARTICLE



The Effect of Turbulence on Dynamic Radar Cross Section of Chaff Clouds

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Abstract

Objective: This research reports the effect of turbulence on the dynamic Radar Cross Section (RCS) of chaff cloud. In the era of modern warfare technologies, most efficacious electronic countermeasure employed by the armed forces of various major powers is the Chaff. Chaff is based on the expulsion of numerous electrical dipoles of different length to cover the broad spectrum of radar frequency. This mechanism helps in deceiving the enemy missile by producing the required RCS. RCS of chaff cloud is a dynamic entity and rely on several aerodynamic factors. **Methodology:** Effects of turbulence on dynamic RCS are studied using Ansys Fluent for aerodynamic blooming simulation and Ansys HFSS for simulation of RCS of the bloomed chaff cloud. **Findings:** The subject of the paper corresponds to the significant effect of turbulence on the expeditious blooming of chaff cloud. The RCS of turbulent flow was higher by 1.5dBsm to 2.5dBsm for 50msec. The turbulence effect has reduced the blooming time of chaff filaments in the range of 25msec - 50msec. **Novelty:** Turbulence plays important role in faster blooming of chaff cloud and achieving minimum threshold RCS required for deception of RF seeker missiles.

Keywords: Chaff; RCS; Turbulence; Modelling and Simulation

1 Introduction

Chaff persist from the ancient stages of Second World War. Chaff cloud is cluster of electrical dipoles that resonates at their respective frequency to generate strong backward scattering return for the requisite RCS^(1,2). RCS of a target is the measure of the backscattered power per unit solid angle respective to the incident power. Mathematically

$$\sigma = \lim_{R \rightarrow \infty} \left(4\pi R^2 \frac{W_s}{W_i} \right) \quad (1)$$

Where W_s and W_i are Scattered and Incident power density respectively; σ is the RCS; R is the Range.

In most practical scenario, there is some motion between the target and radar that causes variation with respect to the frequency and the target aspect. This observed RCS is known as Dynamic RCS. Enemy weapon trace various parameter prior to strike and most prolific feature is the RCS of the earmark. When the enemy missile latches the locus of target, it follows the path. To extricate the aircraft from the missile, chaff cloud is being dispensed by the aircraft which mimic as a false target. The RCS of completely bloomed chaff cloud is comparable or greater than the RCS of the deceived object. The aircraft moves away from the missile locked position, leaving only the chaff cloud in its range to which the missile hits^(1,2). RCS of chaff clouds is given by

$$\sigma = \frac{G^2 \lambda^2}{\pi} \quad (2)$$

where G is the antenna gain.

The fibres are considered to be randomly distributed in three dimensional space with all orientations are equally likely probable. The RCS is averaged over all random orientations with respect to the incident wave. Assuming random orientation of the dipoles and averaging over 4π ,

$$\sigma = 0.172\lambda^2 \quad (3)$$

For N number of dipoles,

$$\sigma = 0.172N\lambda^2 \quad (4)$$

The chaff designed should fulfill three important features

- 1) The RCS of the chaff cloud should be remarkable.
- 2) The chaff cloud should cover the broad range of radar frequency.
- 3) The blooming time of the chaff cloud should be very less.

The blooming of chaff cloud drive through four phases, first is the birth phase of chaff cloud called transient phase, second is bloom phase in which the formation of chaff cloud begins, third is the Mature phase when the requisite RCS of chaff cloud is attained and last is Decay stage^(1,2).

The missile aircraft engagement is very critical in initial few milliseconds. The turbulence can enhance the efficiency of the chaff cartridge in initial engagement and effective break lock. The considerable time required for the blooming and dynamic RCS of chaff fibre must within fraction of second. There are various work has been done related to turbulence. Electromagnetic scattering characteristics of foil in hypersonic plasma turbulence has been reported in⁽³⁾. Various Cutting Edge Turbulence Simulation methods for wind energy and aerospace problems have been reported in⁽⁴⁾. Direct numerical simulation of compressible turbulence in counter flow channel configuration, in which two streams of fluid are brought together from opposite directions is discussed in⁽⁵⁾. Bistatic scattering evaluation method for chaff cloud in airflow is presented in⁽⁶⁾. In⁽⁷⁾, discrete electromagnetic model for the evaluation of Wideband Bistatic Scattering Responses and statistics of chaff cloud is reported. Modelling and simulation of high speed (rotational) release of chaff cloud is studied and reported in⁽⁸⁾. However, in the present paper analysis of turbulence on increasing dispersion efficiency of chaff by varying Turbulent Kinetic Energy (k) is studied and reported in this paper.

2 Turbulence

The paramount factor for rapid blooming of chaff cloud is the turbulent kinetic energy due to aircraft movement. In fluid dynamics, the turbulent flow is the pattern of movement in fluid experiencing chaotic changes in the pressure and velocity. In contrast to the laminar flow, there is irregular fluctuation and mixing among the fluids. Turbulent kinetic energy is the mean kinetic energy per unit mass associated in turbulent flows⁽⁹⁾. Mathematically, in Computational Fluid dynamics environment the turbulent kinetic energy is

$$k = \frac{3}{2}(UI)^2 \quad (5)$$

Where U is the initial velocity magnitude; I is the Initial Turbulence Intensity.

$$I = 0.16(R_E)^{\frac{-1}{8}} \quad (6)$$

Where R_E is the Reynolds Number.

It is used to indicate whether the fluid flow in term of laminar /turbulent. Higher is the Reynolds number, more is the turbulence in the flow

$$R_E = \frac{\rho v L}{\mu} \tag{7}$$

Where ρ is the density of fluid; v is the velocity of fluid with respect to the object; L is the aircraft wing length; μ is the dynamic viscosity of fluid⁽¹⁰⁾.

3 Modelling and Simulation Software

Ansys Workbench, Ansys Fluent and HFSS-IE have been used to analyse the effect of turbulence on dynamic RCS simulation. ANSYS Workbench is used to define the geometry and meshing properties of primitive over which the operation has to be performed. The flowchart is shown in Figure 1 below.

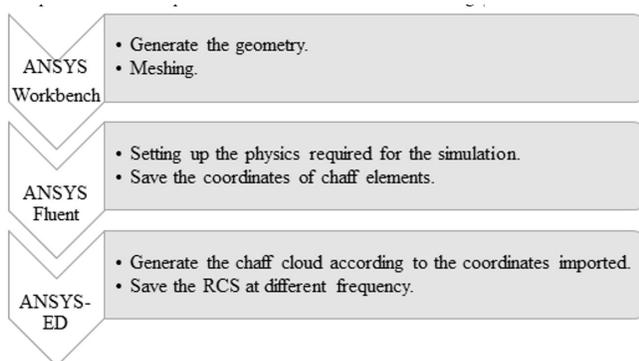


Fig 1. Flowchart of Software

3.1 Ansys Workbench

In Design Modeler, the box type primitive is generated and coordinates are assigned to it. In meshing cell, the physics and solver preference is set to CFD and Fluent respectively to create a virtual environment for the blooming of chaff cloud. The hexahedral mesh of proper size is generated over whole geometry and the parts of geometry are defined as inlet, outlet and walls.

3.2 Ansys Fluent

The model is then exported to the CFD simulation tool for performing the chaff ejection simulation and obtaining the coordinates of chaff elements at a specific time. The proper physics is set by assigning values to various aerodynamic and materialistic parameters to imitate the real visualization of chaff cloud generation. The energy option is enabled in the setting up physics to activate the heat transfer and temperature dependency. Due to high Mach number, the implicit density-based solver is selected and the gravitation force is applied in -y direction. The simulations are computed in transient time manner for fixed discrete time steps which are repeated for a number of times till the required duration is obtained. In each time step, the difference solutions between two successive iterations must be around e^{-3} . Since the solver is density based and the flow is not disaggregated, the absolute velocity formulation is preferred and the momentum equations are the function of absolute velocities⁽¹⁰⁾.

The standard $k - \epsilon$ model with standard near wall treatment is adopted. The inert type elements are injected in group streams in the y-z plane. The velocity of chaff ejection is 35m/s in z-direction while the aircraft movement is in x direction as shown in Figure 2.

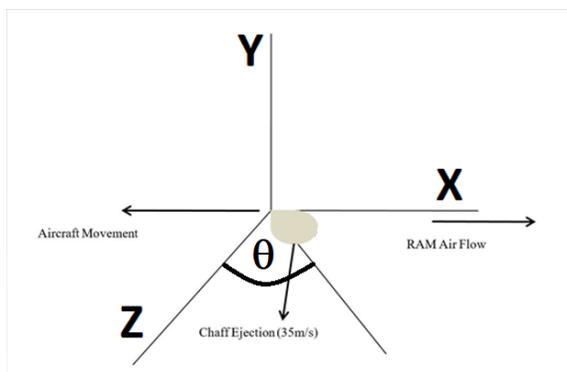


Fig 2. Coordinates systems used for showing Chaff ejection

The effect of turbulent velocity fluctuations on the trajectories of particle is tracked using stochastic tracking by adopting discrete random walk model or eddy lifetime model. The input and output of the simulation box is defined as pressure type, while the discrete phase boundary conditions are defined as escape. The walls of the geometry are provided with the reflect type boundary condition. The particles are reflected in a polynomial manner in both normal and tangential direction. The injections are modeled using non-spherical drag law and the specific shape factor is given according to the diameter of the various chaff element. The pressure acts in the perpendicular direction at input and output box of the model. The standard initialization method is adopted for the field and the initial values are added manually. The first-order transient formulation is selected for the time dependence solution formulations. The spatial discretization for the turbulent related parameters is defined as per first order upwind while for the flow equations, the second-order upwind scheme is selected. The evaluation of gradients is done by adopting least square cell based scheme in which the gradients are calculated between the centroid of one cell to the centroid of another cell. The default values are given to the Courant number and under relaxation factor. After the simulation, the particles are tracked in graphics and coordinates are saved in a file. The Scheme chart for ANSYS Fluent is shown in Figure 3 below.

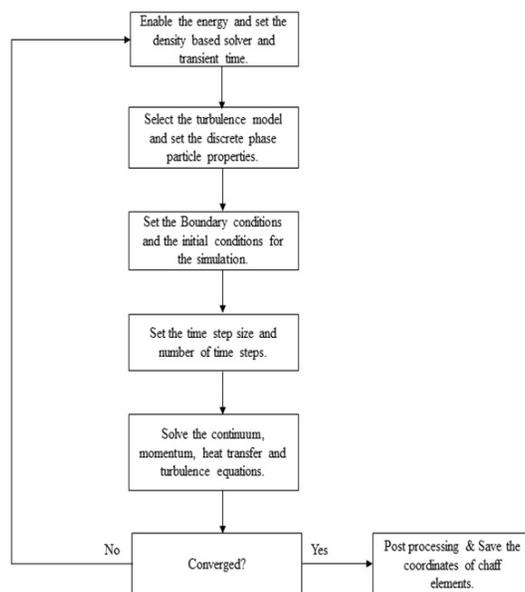


Fig 3. Scheme chart of ANSYS Fluent

3.3 Ansys-ED

HFSS-IE performs surface analysis using Finite Element Method. The python scripts runs in the background to import the excel file of the coordinate position to generate the chaff cloud in HFSS for the calculation of maximum average RCS. The plane incident spherical wave is given as excitation and the infinite sphere far field set up is selected for the calculation of RCS of the chaff cloud. The surface of the chaff fibres is fragmented into number of triangular meshes of lambda refinement 0.15λ to calculate current by applying finite conductivity boundary conditions and excitation.

4 Simulation studies for effect of turbulence on Dynamic RCS of chaff cloud

A scale down version of chaff clouds is performed by taking 1000 elements of four lengths. These lengths are converted to their equivalent shape factor & diameter as shown in Table 1 below. To study the subject of paper, simulation was performed for ideal non-turbulent condition compared to turbulent conditions depending upon the angle in which chaff is dispensed from the aircraft.

Table 1. Different electrical filaments taken for RCS analysis

Equivalent Diameter (μm)	Shape factor	No. of filaments
361	0.1040	250
297	0.1260	250
278	0.1344	250
252	0.1494	250

For evaluation of turbulence, appropriate values of density, air velocity, and viscosity of fluid at heights of 4000 m were given. As shown in Table 2 below the turbulent kinetic energy varies in the range of $17.5 \sim 18.3 \text{ m}^2/\text{s}^2$ instretching from parallel to the perpendicular ejection inclination. The transition to turbulent model for boundary air flow occurs when the Reynolds number is greater than 5×10^5 .

Table 2. Variation of Turbulent Kinetic Energy with different perpendicular ejection inclination

Angle (degree)	R_E	Turbulent Kinetic Energy k (m^2/s^2)
0	573.087×10^5	17.5446
30	561.649×10^5	17.729
45	548.066×10^5	17.75
60	530.410×10^5	17.95
90	487.733×10^5	18.375

The cloud expansion with and without turbulent flow at 50ms are shown in Figures 4 and 5 below respectively.

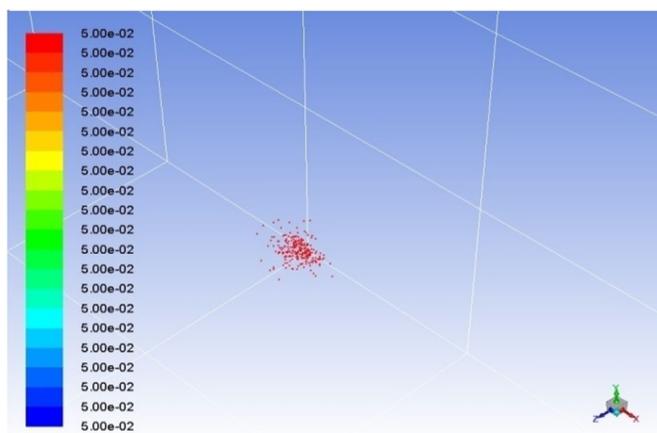


Fig 4. Chaff cloud at 50 msec (Non-turbulent flow)

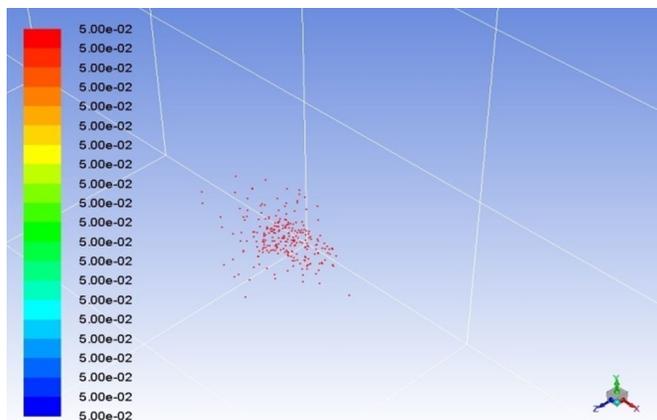


Fig 5. Chaff cloud at 50 msec (Turbulent flow $k=18.375$)

5 Results and Discussion

There are various previous work that has been reported on turbulence as shown but there is no specific work on effect of turbulence on blooming of chaff cloud when the chaff is fired either parallel of perpendicular ejection. Blooming and dynamic RCS of the 1000 chaff elements was simulated for the time span of 50msec and 100msec at different turbulent kinetic energy with ejection angles are shown in Figures 6 and 7 respectively.

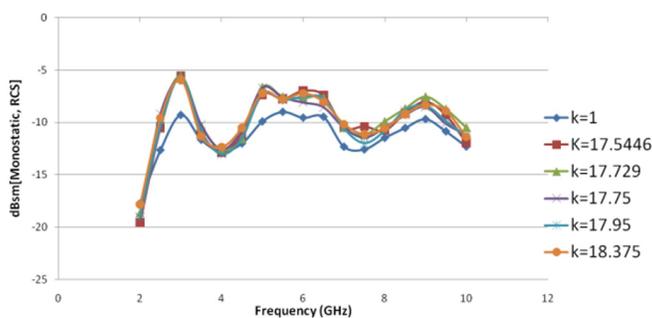


Fig 6. Effect of turbulence on RCS response at 50msec

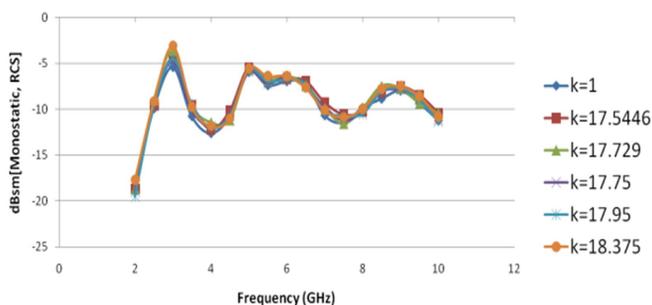


Fig 7. Effect of turbulence on RCS response at 100msec

The RCS of turbulent flow was higher by 1.5 dBsm to 2.5 dBsm for $t=50$ msec. The RCS response of non-turbulent model at $t = 100$ msec become almost identical to the turbulent model RCS response at $t = 50$ msec, with slight divergence of around ± 0.5 dBsm. It can be perceived that the turbulence effect has reduced the blooming time of chaff filaments in the range of 25 msec – 50 msec. While collating the results between turbulence for perpendicular ejection of chaff fibres ($\theta = 90^\circ$) and parallel ejection

of chaff fibres ($\theta = 0^\circ$), it is observed that initially at $t = 100$ msec, RCS response of former was higher than the latter by 0.1 dBsm-1 dBsm. After a certain time both the cases had almost similar responses, it can be sensed from the above fact that the turbulence has greater effect for perpendicular ejection.

6 Conclusion

The turbulence effect has reduced the blooming time of chaff filaments in the range of 25msec - 50msec. It can be observed from figure 7 that the RCS of non-turbulent ($k=1$) chaff cloud becomes equal to turbulent chaff ($k>1$) cloud RCS at 100msec. However, when we observe and compare RCS of non-turbulent ($k=1$) chaff cloud and turbulent ($k>1$) chaff cloud shown in figure 6 with figure 7, it can be observed that the RCS of non-turbulent chaff cloud that we get at 100 msec could be easily get at 50 msec turbulent ($k>1$) chaff cloud. It can be inferred that the turbulence has a pivotal role in dispersal of chaff filaments resulting in surge in inter dipole spacing and RCS values of chaff during initial firing. Original chaff cartridges consist of millions of chaff filaments, this analysis can be further extrapolated to simulate the effect of turbulence in a practical case scenario.

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