Radar Cross Section Calculation of a Wind Turbine Modeled by PEC Canonical Structures

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Abstract

Wind turbines are electrically large and complex objects that act as scatterer for electromagnetic waves. Thus, they may cause performance degradation for radar systems. Radar simulations are useful tools to obtain suitable wind turbine sites around radar bases. Radar cross section (RCS) calculation is an important step in radar simulations. In this work, RCS of a wind turbine which is modeled by canonical structures is calculated analytically and validated with Physical Optics (PO) method.

1. Introduction

Renewable energy sources are getting importance because of the disadvantages of fossil fuels. With the increasing popularity of wind as a renewable energy source, adverse effects of large wind turbines and wind farms on air traffic or defense radar systems are becoming prominent. Sources of these effects are static clutter which arises from the backscattered signal from the turbine structure, and dynamic clutter due to rotational movement of blades. These may cause decreasing probability of detection, increasing false alarm rates or losing tracks for radars [1].

To get maximum benefits from wind energy and avoid these performance degradations on radars, it is very important to determine suitable wind turbine sites that are out of range of the minimum permissible distance from the radar system. Computer simulations, one has been developing by RAPSIM in TUBITAK [2], can be used for achieving this goal and research new methods for masking turbine clutters.

RCS calculations have a key role in radar simulations. In [3, 4], an approximate method is developed to compute RCS of wind turbine tower modeled as a set of cylinders and PO model is used for calculation RCS of the blades. In [5], blades are modeled as PEC flat plates and tower is modeled as finite length cylinder for UHF band. RCS value of a nacelle calculated by PO is added in [6].

In this paper, a wind turbine is modeled by tower and blades. The tower and blades are divided into smaller canonical parts such as cylinders and plates to obtain realistic far field conditions. RCS of these parts are calculated analytically to get minimum computational time, and benefits of this calculation approach for a real-time radar simulator are discussed.

2. RCS Calculations of Wind Turbines

RCS can be used to estimate the effect of a target on a radar system and defined as a measure of power scattered in a given direction when an obstacle is illuminated by an incident plane wave. It can be formulated by

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{\left|E^s\right|^2}{\left|E^i\right|^2} \tag{1}$$

where E^s is the scattered field and E^i is the incident field at the target, respectively [7].

As given in equation (1), general definition of RCS assumes an infinite range that provides a plane wave excitation. The plane wave can be approximated by well-known far field conditions which is given by

$$R_{farField} \simeq \frac{2D^2}{\lambda} \tag{2}$$

where D is the maximum dimension of the obstacle, $R_{farField}$ is the minimum far field range and λ is wavelength. Far field ranges are calculated and presented for some modern wind turbine models at typical radar bands in Table 1.

Table 1. Far field ranges of turbines for radar frequencies

Turbine		Far Field Range (km)		
Model	**Total Height**	**L (1.5 GHz)**	**S (3.0 GHz)**	**C (6.0 GHz)**
ENERCON E-44	85 m	72,25	144,50	289,0
NORDEX N90	124 m	153,76	307,52	615,04
SIEMENS SWT 2.3 113	135 m	182,25	364,50	729,0
VESTAS V 112	174 m	302,76	605,52	1.211,04

Depending on the calculated far field ranges, it is clear that these distances cannot be performed to obtain plane wave illumination on wind turbines for realistic RCS applications and radar performance analysis scenarios especially at higher frequency bands. To achieve this problem, turbine can be modeled small enough structure parts which easily provide realistic far field distances. After constructing the turbine with these parts, total RCS of the turbine can be calculated by summing their individual RCS contributions for an observation point. Method of moments (MoM), finite element method (FEM), PO or geometrical optics (GO) methods can be used for RCS calculations of these parts. Small size of these parts may avoid suffering from long computational times or high memory requirements of those computational methods. However, these methods need realistic computer aided design (CAD) models of the turbine parts that are generally difficult to obtain since they are usually considered as confidential by turbine manufacturers. Even if one gets a realistic CAD model data or try to use a common one, it must be rearranged for every single different broadside angle of turbine and rotational movement of blades. But, a scattering algorithm based on an analytical model may be more suitable for RCS calculation of the turbine model parts, because it is faster than any numerical approach, works different broadside angles of turbine without making any modification on model, easily manages blade rotation effects and expands for wind farms.

Therefore, an analytical solution, which provides far field condition initially, seems much more suitable than any numerical methods for real-time radar simulations, especially for wind farms which are affected by wind direction changings and illuminated by different radars. To construct such an analytical solution, a wind turbine is modeled by perfectly electrical conducting (PEC) canonical structures. Suggested canonical model does not contain nacelle and nosecone for the sake of simplicity, due to tower and blades are the largest source of scattering. The nacelle can be considered to be significant scatterer for 90° broad side angle and nosecone is usually insignificant at all angles [8]. As shown in Fig. 1, blades and tower are modeled by plates and cylinders which are small enough to achieve realistic far field conditions.

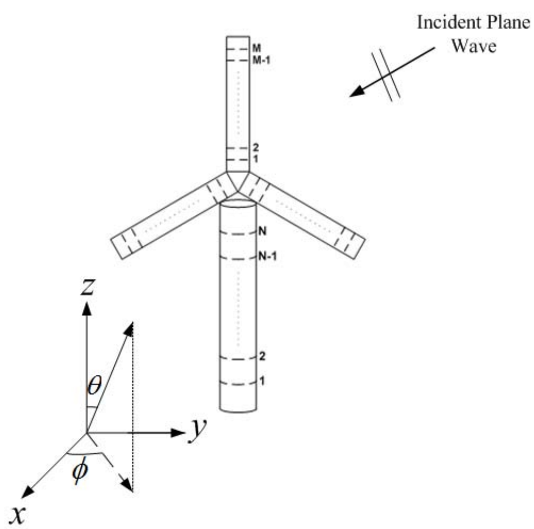

Fig. 1. Wind turbine model segmented by canonical structures

Bistatic RCS of a finite length PEC plate for TE and TM cases are given in equations (3-5) [9]

$$\sigma_{3D}^{TE} = 4\pi\left(\frac{ab}{\lambda}\right)^2\left(\cos^2\theta_s\sin^2\phi_s+\cos^2\phi_s\right)sinc^2\left(X\right)sinc^2\left(Y\right) \quad (3)$$

$$\sigma_{3D}^{TM} = 4\pi\left(\frac{ab}{\lambda}\right)^2\left[\cos^2\theta_i\left(\cos^2\theta_s\cos^2\phi_s+\sin^2\phi_s\right)\right] \times sinc^2\left(X\right)sinc^2\left(Y\right) \quad (4)$$

$$X=\frac{ka}{2}\sin\theta_s\cos\phi_s\,,\; Y=\frac{kb}{2}\left(\sin\theta_s\sin\phi_s-\sin\theta_i\right) \quad (5)$$

where a and b are dimensions of the plate, θ_i is the incident angle, θ_s and $_s$ are the scattering angles in spherical coordinates, and k is the wavenumber in free space.

Bistatic RCS of a finite length PEC cylinder for TE and TM cases are given in equations (6-8) [9, 10]

$$\sigma_{3D}^{TE} = \frac{4l^2}{\pi}\sin\theta_i\left|\sum_{n=0}^{\infty}\varepsilon_n b_n\cos\left(n\phi\right)\right|^2 sinc^2\left[\frac{kl}{2}\left(\cos\theta_i+\cos\theta_s\right)\right] \quad (6)$$

$$\sigma_{3D}^{TM} = \frac{4l^2}{\pi}\frac{\sin^2\theta_s}{\sin^2\theta_i}\left|\sum_{n=0}^{\infty}\varepsilon_n a_n\cos\left(n\phi\right)\right|^2 sinc^2\left[\frac{kl}{2}\left(\cos\theta_i+\cos\theta_s\right)\right] \quad (7)$$

$$a_n=\frac{-J_n\left(ka\sin\theta_i\right)}{H_n^{(2)}\left(ka\sin\theta_i\right)},\; b_n=\frac{-J_n'\left(ka\sin\theta_i\right)}{H_n^{(2)\prime}\left(ka\sin\theta_i\right)},\; \varepsilon_n=\begin{cases}1, & n=0\\ 2, & n\neq 0\end{cases} \quad (8)$$

where a and l are radius and length of the cylinder; respectively. J_n represents Bessel functions of the first kind, $H_n^{(2)}$ Hankel functions of the second kind, and the prime (′) denotes differentiations.

RCS of the turbine model (σ_T) can be calculated by coherent summation of the reflected fields from the individual parts [11]

$$\sigma_T=\left|\sum_{n=1}^{(N+3M)}\sqrt{\sigma_n}\exp\left\{-i\psi_n\right\}\right|^2 \quad (9)$$

where ψ_n is the phase due to the two-way distance between radar and the segment.

Analytical and canonical model (CAM) bistatic RCS solutions of a 40m x 4m PEC plate for TE and TM cases are compared in Fig. 2 and Fig. 3. The origin of the coordinate system is the center of the plate. In canonical model, the plate is constructed by plates having 1m x 4m dimensions. In all simulations, elevation angle theta is 90°.

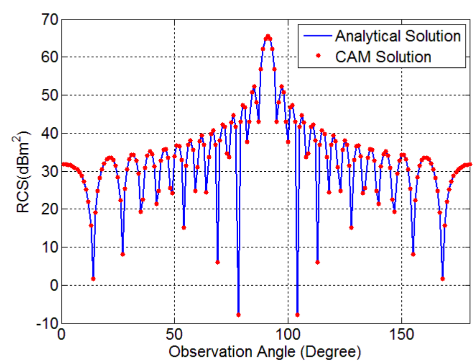

Fig. 2. Bistatic RCS solution of a PEC plate for TE case at 1 GHz

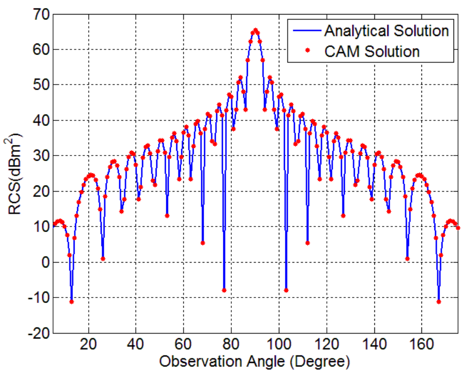

Fig. 3. Bistatic RCS solution of a PEC plate for TM case at 1 GHz

Analytical and canonical model bistatic RCS solutions of a PEC cylinder for TE and TM cases are compared in Fig. 4 and Fig. 5. Length of the cylinder is 60 m, and radius of the cylinder is 2 m. The origin of the coordinate system is the center of the cylinder. In canonical model, the cylinder is constructed by smaller cylinders which have 10m length and 2m radius.

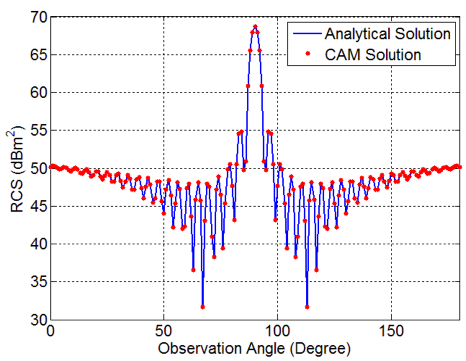

Fig. 4. Bistatic RCS solution of a PEC cylinder for TE case at 1 GHz

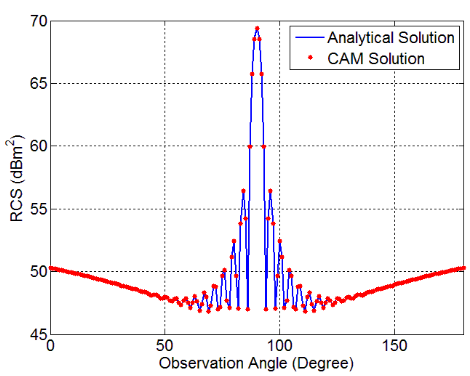

Fig. 5. Bistatic RCS solution of a PEC cylinder for TM case at 1 GHz

PO and canonical model bistatic RCS solutions of the 40m x 4m blades for TE and TM cases are compared in Fig. 6 and Fig. 7. In canonical model, blades are modeled by plates which sizes are 1m x 4m. PO and canonical model bistatic RCS solutions of a wind turbine model which has 60 m tower and 40 m blade length, for TE and TM cases are given in Fig. 8 and Fig. 9. Moreover, PO and canonical model monostatic RCS solutions of the model are presented in Fig. 10. In these simulations, the origin of the coordinate system is chosen as the beginning of the vertical plate.

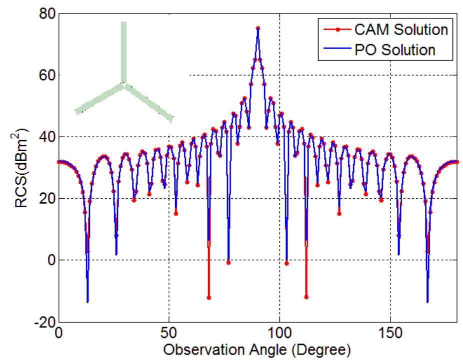

Fig. 6. Bistatic RCS solution of the blades for TE case at 1 GHz

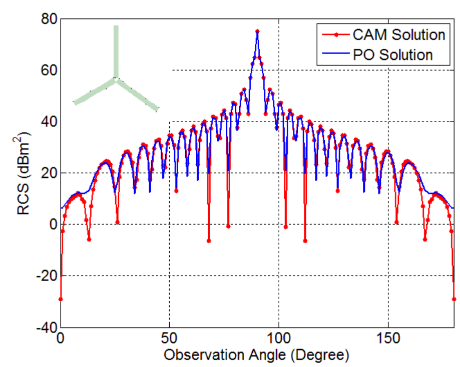

Fig. 7. Bistatic RCS solution of the blades for TM case at 1 GHz

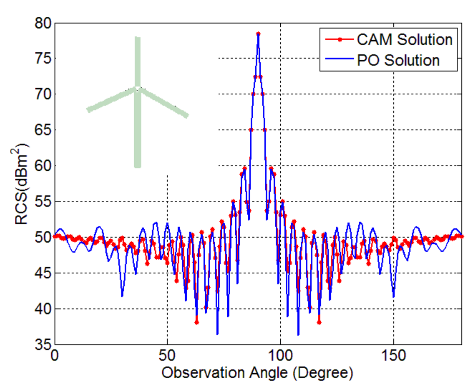

Fig. 8. Bistatic RCS solution of the turbine model for TE case at 1 GHz

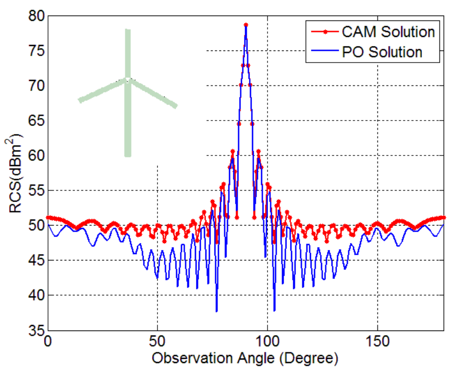

Fig. 9. Bistatic RCS solution of the turbine model for TM case at 1 GHz

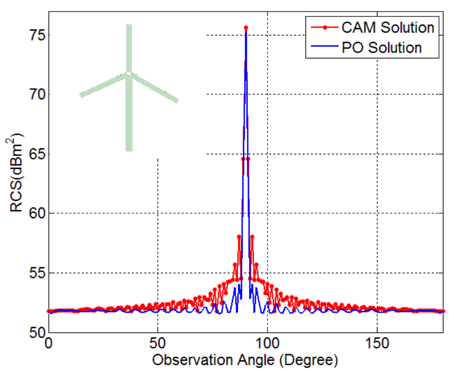

Fig. 10. Monostatic RCS solution of the turbine model at 1 GHz

3. Conclusions

In this paper, an analytical RCS calculation approach is presented for electrically large wind turbines which can be modeled by smaller PEC canonical structures such as plates and cylinders. These smaller parts perform realistic far field conditions for radar applications. CAM results obtained for blades and turbine are compared to PO results. It is seen that there is a good agreement between results. Analyzing effects of terrain, using dielectric material for blades, improving turbine model, and applying CAM to a wind farm are planned as future works.

4. References

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