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Radar micro-Doppler of Wind Turbines: Low-Frequency Polarimetric Extension of Simplified Analytical Model

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***Abstract*—A simplified polarimetric model for radar signal scattering on wind turbines (WT) is proposed, which can be used for interpretation of observation in time and Doppler domains. This model uses representation of real WT as slowly rotating linear wire structures. The earlier proposed model has been extended to more general cases of WT with arbitrary orientation and full polarimetric observations in mono- and bi-static cases, which can be used for analysis of low-frequency signals scattering. It gives a possibility to estimate the influence of scattered on WT electromagnetic waves not only on radars but also on communication links.**

***Index Terms*—wind turbines, polarimetric Doppler radar, micro-Doppler, wave scattering**

I. INTRODUCTION

The wind turbine structures and the wind farms are affecting the existing radar systems such as air-traffic control and weather radar networks because of the strong electromagnetic interference known as wind turbine clutter (WTC). To improve power production, the size of blades and the height of new WTs are constantly increasing. However, this improvement has affected the field of radar and communications links by giving rise to certain phenomena such as shadowing, scattering, and multi-path propagation. As result, the signal to noise plus clutter ratio for radar targets decreases, reducing the range of operations. The motion of the wind turbines make it difficult to suppress these effects using existing ground clutter mitigation techniques. Thus, there is a need to scrutinize these dynamic effects, which result in specific micro-Doppler signatures of WT, to be able to mitigate them.

The existing WTC models are based either solely on the RCS of the WT's or use computationally-costly and complex electromagnetic simulation techniques (e.g. [1]) that make them not applicable for express-analysis and interpretation of experimental data. A simplified model of electromagnetic scattering on WT for the analysis of micro-Doppler structure of radar received signals has been proposed in [2]. This model represents the WT as slowly rotating linear wired construction, blades are modeled as a non-interacting combination of very thin finite length linear wires. Original model has been used for the analysis of micro-Doppler effect when the rotation plane of WT is parallel to radar line of sight and did not take into account the polarization of radar signals. It also used time domain simulation of WT response for monochromatic incident wave and did not provide the possibility to simulate realistic radar range profile of WT. Proposed in [3] range segmentation for simulations of WT's radar range profiles extended the original model.

This paper discusses the extensions of simplified electromagnetic model of WT [2] for the simulation of a WT's full polarimetric scattering matrix in monostatic and bi-static cases. The derived polarimetric extensions are mostly applicable for the VHF band when the wavelength (1-10m) is comparable with the size of the WT blades. Together with a presence of electrically thin metal construction elements (lightning protection wires) it results in different from microwaves scattering mechanisms and in applicability of proposed simplified model extension to polarimetric data analysis at low frequencies [4].

The paper is organized as follows. Section II presents the low-frequency polarimetric extension of simplified WT model for mono- and bi-static scattering cases, the Section III concludes the paper.

II. POLARIMETRIC EXTENSION OF SIMPLIFIED WT'S MODEL

From general consideration of the geometry of scattering problem it can be assumed that at low frequencies (VHF band), when the influence of surface scattering effect becomes low and electrically thin wired metal construction elements play dominant role, the original model [2] can be extended to more general case of arbitrary azimuthal orientation of WT rotation plane relatively to a radar and to full polarimetric description of scattered signal in mono- and bi-static cases. Here we present the analysis and resulting theoretical relations. The detail validation of proposed approach using experimental data has still to be done and is out of the scope of this article.

The goal of this model is to predict the behavior of radar returns in the far-field region, and to interpret radar observations in time and Doppler domains. Initial assumptions allow analytical derivation of basic closed-form solutions with less computational time and efforts.

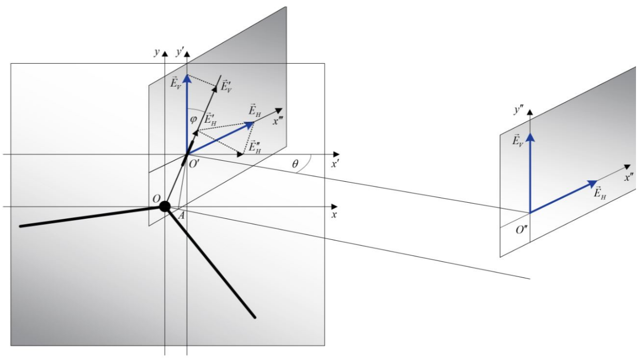

Fig. 1: Geometry of the model design in monostatic case.

A. Polarimetric Model for Mono-Static Case

Consider a coordinate system ($O = x, y, z$) and a blade as a wire that satisfy the thin-wire dipole approximation [5]. The WT's center of rotation is placed at the origin of the coordinate system as shown in Fig. 1. Angle ϕ denotes an orientation angle of the WT's blade in the rotation plane, and θ denotes an aspect angle between the rotation plane and radar line of sight.The finite length wire is sub-divided into a number of infinitesimal dipole length of dz'. One of that dipoles is placed at $O' = x', y', z'$ which is at a distance $z' \in \left[0, L\right]$ from the rotation center O along the blade. The radar is located at a point with coordinates (x'', y'', z'') where the (x'', y'') plane oriented with an aspect angle θ to the plane of rotation (x', y') at a distance z_0 in a radar's far field.

Follow to [5], the integral electric field scattered from all the infinitesimal elements over the wire length L can be written as

$$E_\phi = \left[j\eta \frac{ke^{-jkz_0}}{4\pi z_0} \sin\phi \right] \left[\int\limits_L I_e(x', y', z') e^{jkz' \cos\phi} dz' \right] \tag{1}$$

where two multipliers within rectangle brackets are known as *element* and *space factors*, respectively. The term z_0 is the distance between the center of the coordinates and the observation point. The space factor is a function of the current distribution along the linear wire structure.

For the case of aspect/azimuth angle $\theta = 0°$ in [2] has been derived following relation

$$dE_\phi^{BS}(\phi, z') \sim j\eta \frac{ke^{-jkz_0}}{4\pi z_0} E_\phi(r) \sin^2\phi e^{+j2kz' \cos\phi} dz' \tag{2}$$

To extend the model into a 3-D model, the equation has to include the WT-radar aspect angle θ, polarization, and relations for phase differences relatively to the center of coordinates O. The amplitudes of the resulting back-scattered field can be calculated using trigonometric relations for angles as in Fig 1.

$$E_{VV}^S = E_V \cos^2\phi(t), E_{HH}^S = E_H \sin\theta \sin\phi(t) \tag{3}$$

Similarly, the displacements of the infinitesimal dipole, which is placed at distance z' along the blade from the rotation center:

$$\Delta R_{VV}^S = z' \cos\theta \sin\phi(t); \Delta R_{HH}^S = \Delta R_{VV}^R \tag{4}$$

where $0 \leq z' \leq L$, L is the length of the WT blades. Using these relations, the following equations for the polarization state back-scattered field can be derived

$$\begin{bmatrix} E_V^S \\ E_H^S \end{bmatrix} = \mathbf{S} \begin{bmatrix} E_V^T \\ E_H^T \end{bmatrix} = \begin{bmatrix} S_{VV} & S_{VH} \\ S_{HV} & S_{HH} \end{bmatrix} \begin{bmatrix} E_V^T \\ E_H^T \end{bmatrix} \tag{5}$$

where the polarization scattering matrix of blades equals to

$$\mathbf{S} = \sum_{n=1}^{3} \int\limits_0^L \mathbf{S}(\phi(t) + \Delta\phi_n, \theta, z') dz' \tag{6}$$

The elements under integrals are equal to

$$\begin{aligned} d\mathbf{S}_{(\phi,\theta,z')} &= A(z') \cdot dz' \\ &\times \begin{bmatrix} \cos^2\phi(t) & \cos\phi(t)\sin\phi(t)\sin\theta \\ \cos\phi(t)\sin\phi(t)\sin\theta & \sin^2\phi(t)\sin^2\theta \end{bmatrix} \end{aligned} \tag{7}$$

where

$$A(z') = j\eta \frac{e^{-jkz_0}}{4\pi z_0} \cdot \exp(+j2kz' \sin\phi(t) \cos\theta) \tag{8}$$

Here $\Delta\phi_n = -120°, 0°, 120°$ for $n = 1, 2, 3$ are differences in the orientation angles between blades for the case of three-blades WT.

B. Polarimetric Model for Bi-Static Case

Geometric representation of the model design for bi-static case is presented in Figure 2. The red and green dashed lines denote the phase front planes of incident and scattered radar signals, respectively, the blue line - the wind turbine blades plane of rotation. θ_i and θ_s denote angles between this plane of rotation and propagation directions of incident and scattered waves, respectively.

Using the similar analysis as in monostatic case, the phase difference between the incident field and the field scattered from infinitesimal dipole at the distance of z' along the blade wire from the origin of coordinate system O can be found as

$$\Delta\phi = k[\Delta z_i - (-\Delta z_s)] \tag{9}$$

where $k = 2\pi/\lambda$ is wavenumber,

$$\Delta z_i = z' \sin\varphi(t) \cos\theta_i \tag{10}$$

$$\Delta z_s = z' \sin\varphi(t) \sin(90 - \theta_i) = z' \sin\varphi(t) \cos(\theta_S) \tag{11}$$

and, finally,

$$\Delta\phi = kz' \sin\varphi(t)(\cos\theta_i + \cos\theta_s) \tag{12}$$

The backscattering field in bi-static case are also defined as in (5) and (6), but the partial (differential) polarization scattering matrix (7) in this case has to be defined as follow

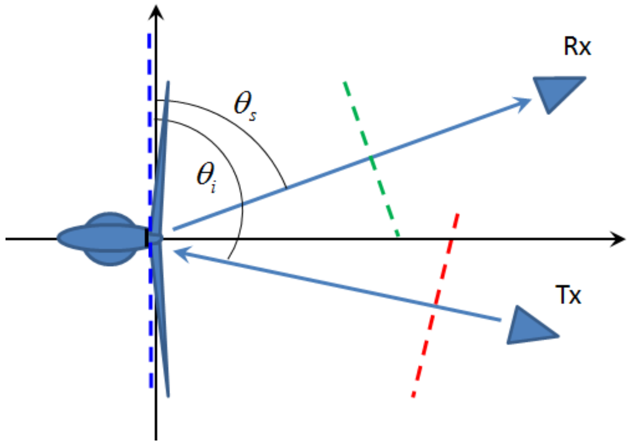

Fig. 2: Geometry of the model design in bi-static case.

$$d\mathbf{S}_{(\varphi,\theta,z')} = j\eta\frac{e^{-jkz_0}}{4\pi z_0}\cdot e^{+jkz'\sin\varphi(t)(\cos\theta_i+\cos\theta_s)}dz'$$
$$\times\begin{bmatrix} \cos^2\varphi(t) & \sin\varphi(t)\cos\varphi(t)\sin\theta_i \\ \sin\varphi(t)\cos\varphi(t)\sin\theta_s & \sin^2\varphi(t)\sin\theta_s\sin\theta_i \end{bmatrix} \tag{13}$$

As expected, for the bi-static case takes place the non-equality of cross-polarized components of the polarization scattering matrix $S_{HV} \neq S_{VH}$: the related to rotational angle $\varphi(t)$ components are equal, but they are multiplied with sinusoidal functions of different azimuthal angles, which define the propagation direction of incident θ_i and scattered θ_s signals.

C. Simulated Results

An examples of the simulated spectrograms (plots of received signals on the plane Doppler frequency vs slow time) of the polarization scattering matrix elements of WT that calculated on the frequency 600 MHz for mono-static case ($\theta_i = \theta_s = 60°$) and for bi-static case with angles $\theta_i = 30°$ and $\theta_s = 60°$ are shown in Fig. 3 and Fig. 4 correspondingly. The height of simulated WT set to be 91m, the blade length - 12.7m. For this simulation a radar pulse repetition frequency (PRF) set to 1 kHz, the Doppler processing done by the coherent integration of 256 pulses with Hamming window. Sequential in slow time spectra have been calculated using 99% overlapped moving window.

As soon as the model simulates WT's blades as polarization-anisotropic thin wires, the continuous Doppler flashes occur only at VV channel when one of blades is vertically oriented and perpendicular to the radar line of sight. The HH and cross-polarized channels present only amplitude-modulated sinusoidal patterns that relates to the scattering on the blades ending points. For the presented simplest case, when every blade simulated as a one thin wire, the positive and negative micro-Doppler patterns are symmetric around the zero Doppler with a time shift for 1/6 of rotation period. It agrees well with observations and previous models (e.g. [1]). More complex models, when a blade modeled as a set of angularly distributed or even spatially-displaced thin wires, can be used for better reproduction of WT's blade geometry and observed micro-Doppler patterns ([2]). The extended spiky continuations of Doppler flushes that are visible in figures in VV channels are the model artifacts (side lobes of strong signals' Doppler processing) and can be suppressed with careful selection of dynamic range for results representation or with including in simulation a noise component with realistic level.

Unlike the mono-static scattering case, the off-diagonal elements of polarization scattering matrix of bi-static scattered signals need not to be the same, as can be seen from Fig. 4. For simulated case the VH polarization shows a bit stronger signal strength than the signal with HV polarization.

Simple analysis of simulated results for both mono- and bi-static cases shows that for the HH polarization the locations of most strong amplitudes of signals in time and frequency are shifted relatively to other polarizations. This follows from the rotation of the blades with anisotropic sensitivity to H and V polarizations. As result, for the suppression of WT introduced interferences in low frequency radar and communication systems this time shift and difference in Doppler pattern in different polarimetric channels has to be taken into account.

III. CONCLUSION

The low-frequency polarimetric extension of the simplified WT model [2] has been developed for arbitrary orientation of a radar and WT's rotation plane, including mono- and bi-static cases. The derived extension is based on general consideration of the geometry of scattering problem. It assumes that at low frequencies (VHF band), when the influence of surface scattering effect is lower and electrically thin wired metal construction elements play dominant role, it is possible to model a WT as slowly rotating linear wired construction. Within this model blades are modeled as a non-interacting combination of very thin finite linear wires. An examples of WT's polarization scattering matrix simulated with the model were presented and briefly discussed.

The detail validation of proposed approach, assumptions and model applicability for different frequency bands are beyond the scope of this article and has still to be done using experimental data. This model can be used for the analysis of scattered on WT radar and communication signals, interpretation of experimental data in time and micro-Doppler domains.

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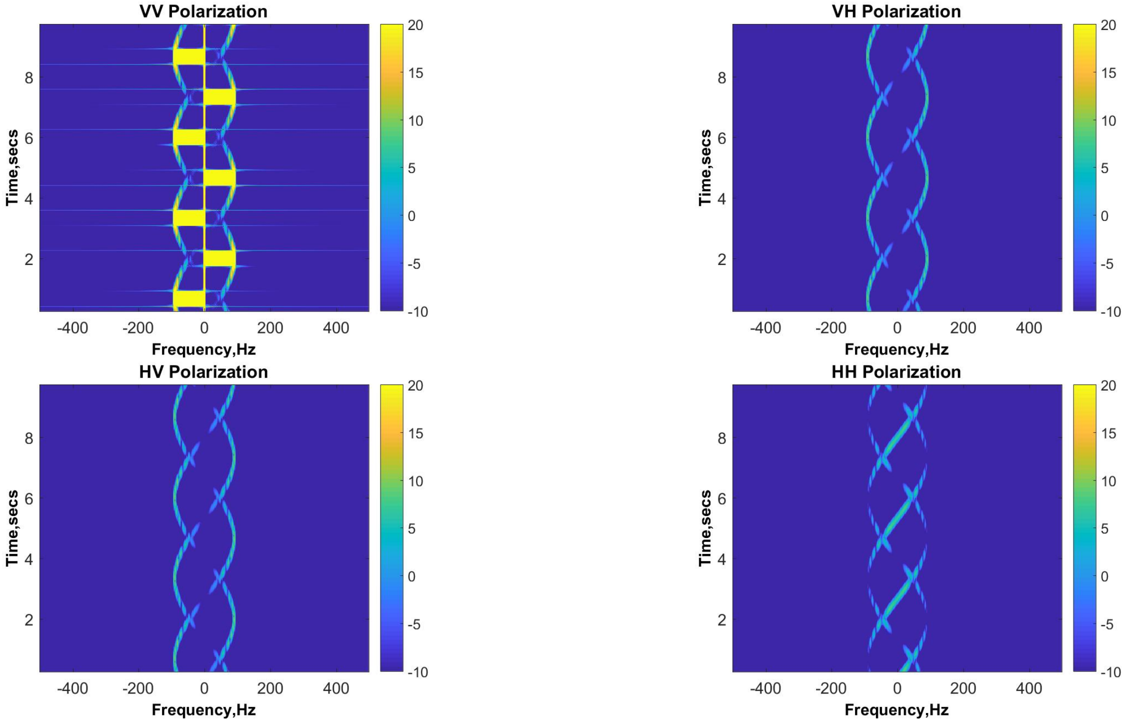

Fig. 3: Spectrograms of polarization channels for monostatic case ($\theta_i = \theta_s = 60°$).

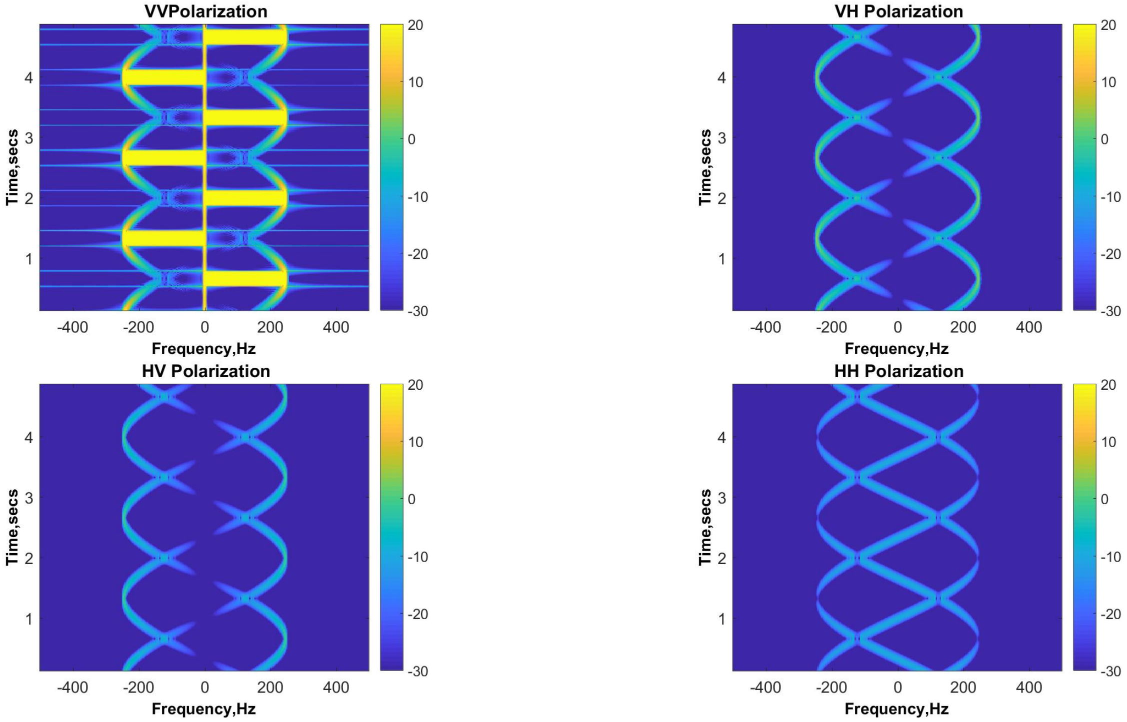

Fig. 4: Spectrograms of polarization channels for bi-static case ($\theta_i = 30°$, $\theta_s = 60°$).