Time-frequency Spectrum and Path Loss by Wind Turbine Forward Scattering

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Abstract— Diffraction loss and deviation of the Doppler spectrum caused by a wind turbine (WT) rotor is analyzed by using a one-dimensional Fresnel diffraction approach applied to the forward scattered signal. To characterize performance degradation of radar and communication systems by a WT, forward scatter path loss and the relative phase shift of the received signal are investigated. Theoretical results are verified by comparison with Uniform Theory of Diffraction (UTD) simulations obtained by FEKO. A joint time-frequency analysis is performed using Short Time Fourier Transform (STFT) to obtain localized time-dependent frequency information about the Doppler deviation.

1. INTRODUCTION

Serious concerns have been raised in recent years about the effects of the growing number of wind turbines on existing radio communication systems [1]. The performance of radar and communication systems can be significantly deteriorated owing to the interference caused by scattering, diffraction and near-filed effects of a nearby WT. Moreover, the rotating blades of the electrically large WT introduce a time variant deviation of the Doppler return, which can cause serious radar clutter problems. Most of the efforts to characterize the signal degradation caused by a WT have focused on the backscatter region [2], while the WT forward scatter investigations have concentrated mainly on the shadowing and range effects in the context of interference with radio and TV broadcast stations as well as with navigation systems and weather radars [3, 4].

In this paper we present an approximation for the calculation of the time variant diffraction induced path loss and phase modulation in the forward scatter region, if the line-of-sight path is obstructed by the rotor swept area of a WT. This scenario is particularly true for weather radars. A one-dimensional Fresnel diffraction approach is applied to a WT rotor in specular direction (head-on view along rotor axis). The rotor blades are assumed to be opaque. The time variant diffraction induced path loss and phase modulation are determined. These calculated values are then used for a time frequency analysis based on STFT to obtain the time variant deviation of the Doppler spectrum along with time-varying motion dynamic features of the received signal. For a radar system, the signal is diffracted twice at the WT blades. To account for the round trip, the one way path loss and phase modulation is multiplied by a factor of 2.

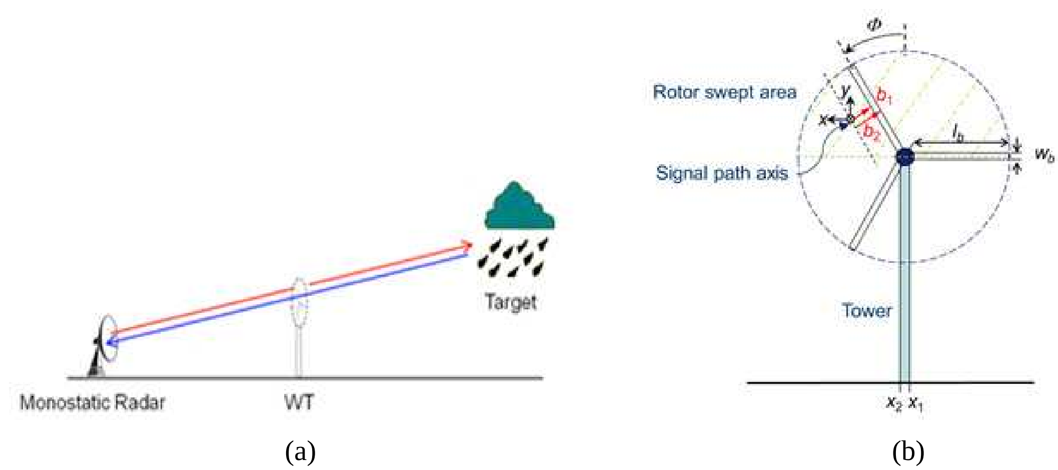

Figure 1: (a) WT obstructing a weather radar. (b) Plane of obstruction — WT in specular direction (head-on view along rotor axis. Shaded part represents the obstruction zone.

2. PATH LOSS AND TIME FREQUENCY SPECTRUM DETERMINATION

Figure 1(a) shows a WT obstructing a radio link. We assume the simplest interference scenario of a signal path cutting the plane of obstruction inside the upper half of rotor swept area (above nacelle) [5]. The signal is periodically obstructed by the rotating blades and hence a time variant Doppler deviation of the received signal is observed. The impact of the static WT tower is neglected. For the simplification of calculations, the blades are assumed to be of rectangular shape in the plane of obstruction. Furthermore, only a single blade with infinite length is considered for the aforementioned simplest interference scenario. We use a one dimensional Fresnel diffraction approximation along a horizontal axis perpendicular to the line-of-sight path (Figure 1(b), origin of x-and y-coordinate aligned with the axis of the signal path in the plane of obstruction) [6].

The amplitude of the electric field at a target located on the axis of the signal path is given by

$$E_p = \frac{E_u}{\sqrt{2}} \left\{ [C(\nu) - jS(\nu)]_{\nu_{b2}}^{+\infty} + [C(\nu) - jS(\nu)]_{-\infty}^{\nu_{b1}} \right\} \tag{1}$$

where E_u is the electric field amplitude at the target in the absence of the obstruction. C and S are the well-known Fresnel integrals. ν is a dimensionless aperture coordinate given as

$$\nu_{x1/2} = \left[-\sqrt{x_0^2 + y_0^2} \cdot \sin\left(\phi + \arctan \frac{x_0}{y_0} \right) \pm \frac{w_b}{2} \right] + \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2} \right)} \tag{2}$$

where d_1 is the distance between the radar site and the WT, d_2 is the distance between the WT and the target, λ is the wavelength of the radar signal, x_o and y_o are the coordinates at the rotor axis and w_b is the blade width. The $+$ sign is applicable for v_1 and the $-$ sign for v_2. A detailed description of this approach can be found in [7]. The results obtained are verified with 3D field solver using Uniform Theory of Diffraction (UTD) method and software package FEKO. The time frequency spectrum is obtained by the short time fourier transform (STFT) of the received time domain signal.

3. RESULTS AND DISCUSSION

The diffraction path loss is calculated at a frequency of 1.30 GHz, which is typically used for weather radars. The WT model used for this investigation has three blades, each with a length of 64 m. The width of the blade at the point where the signal path cuts through the plane of obstruction is assumed to be $w_b = 1.5$ m. A blade rotation speed of 15 rpm is assumed. The signal path is set to be 60 m above the rotor axis (close to the tip of the blade). The WT is at $d_1 = 500$ m away from the transmitter and the receiver is located at 8000 m ($d_2 = 7500$). The one way diffraction induced loss ($\Delta\alpha d$) and the phase shift ($\Delta\beta d$) at 1.3 GHz vs rotation angle Φ are shown in Figures 2(a) and (b). For a radar system, these values have to be multiplied by a factor of 2. For $\Phi = 0$ the upper blade is oriented vertically. At $\Phi = 60°$ this blade is as far from the axis of the signal path

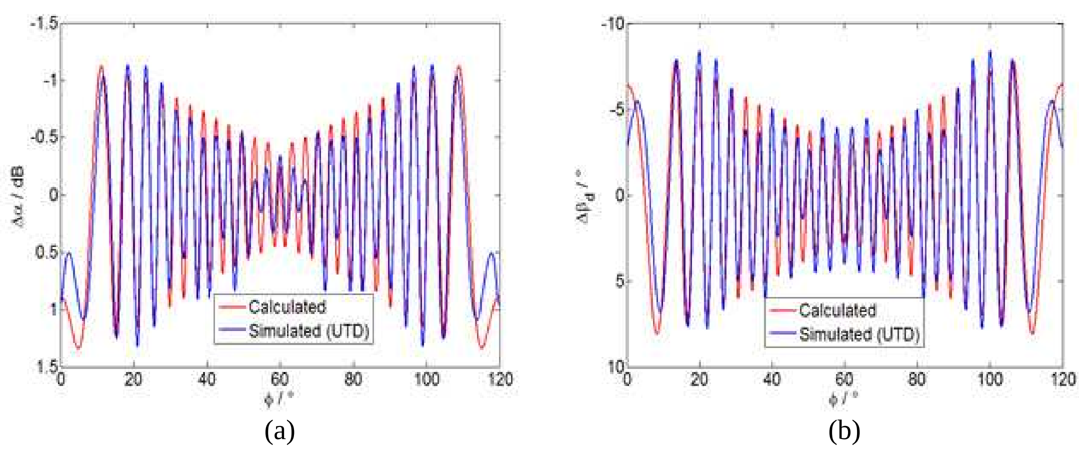

Figure 2: Impact of 3-blade rotor vs rotor angle Φ at 1.3 GHz: diffraction induced one way (a) loss and (b) phase shift for $d_1 = 500$ m and $d_2 = 7500$ m.

as the next blade following in clockwise direction. Thus, all graphs show an even symmetry along Φ for every 60°. The calculated values are verified by comparison with UTD simulation results obtained by software package FEKO.

The comparison in Figure 2 shows a slight disagreement between the calculated and simulated curves. This can be attributed to the scattering at the edges of the blade, which is not considered in our theoretical approach. Moreover, FEKO simulations are carried out with three rotor blades, whereas, the theoretical model only considers a single infinite long blade. At values of Φ around 60°, the next blade which is not considered in the theoretical model is approaching the line of sight and hence diffraction effects of both the blades appear to be significant rather than just the one accounted for. However, for most values of Φ, the two results agree with each other.

Figure 3 shows the maximum value of $\Delta\alpha_d$ for values of d_1 ranging from 500 m to 7500 m. The distance of the WT from the tranmistter (d_1) is varied keeping the overall link distance constant at $d_1 + d_2 = 8$ km. The lowest value of diffraction loss is observed when the WT is located midway between the transmitter and the receiver ($d_1 = d_2 = 4000$ m). As the location of the WT is moved closer to either the transmitter or the receiver, the diffraction loss starts to increase. Due to symmetry, d_1 and d_2 can be interchanged. This underlines the importance of keeping the WT considerably far from a communication system.

The Doppler deviation introduced by the rotating blades can be characterized by the time frequency spectrum of the received signal. A Hamming window of 256 samples for a sampling frequency of 1 kHz is used to obtain the STFT of the received time domain signal. Figure 4 shows the spectrum of the received signal ($d_1 = 500$ m, $d_2 = 7500$ m). For a rotational speed of 15 RPM, a single rotation of one blade is completed in 4 seconds. Noticeable sinusoidal tracks are visible. At low values of Φ, one blade is in close proximity to the line of sight, obstructing the first few Fresnel zones. This gives rise to a strong low frequency component. As the blade rotates, its distance from the signal axis increases and it is cutting through a higher order Fresnel zones at a given time span, introducing higher frequency components with a peak ocurring at $\Phi = 60^\circ$. Beyond this angle, the next blade starts approaching the line of sight, moving towards Fresnel zones of larger sizes (lower order Fresnel zones) thus introducing more components of lower frequencies. Overall, a significant

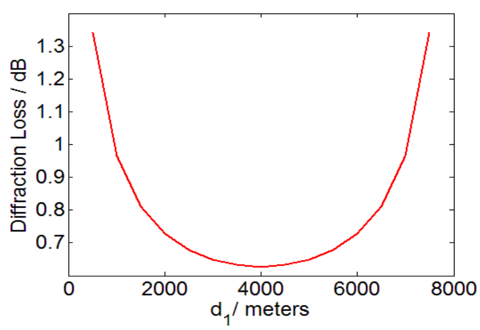

Figure 3: Variation of maximum one-way diffraction loss with changing values of d_1.

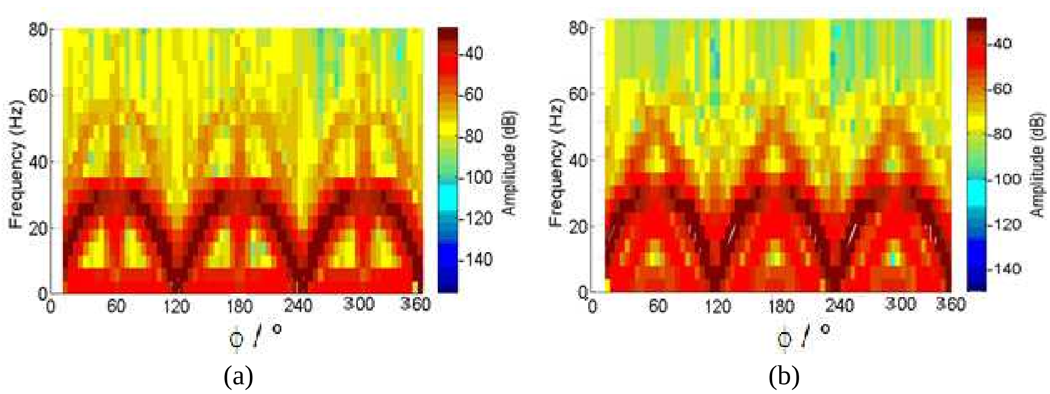

Figure 4: Two-Way Normalized time-frequency spectrum at 1.3 GHz for $d_1 = 500$ m and $d_2 = 7500$ m. (a) Calculated. (b) Simulated.

Doppler deviation of up to 55 Hz is observed. For a Doppler radar, this corresponds to a target velocity of 6.3 m/s. A weather radar, like all Doppler radars, relies on Doppler-shifted radar returns for the estimation of wind speed. Doppler deviation caused by WT blades will therefore lead to inaccurate wind measurements.

The investigations presented in this paper so far have ignored the ground plane effects. 3D radars like weather radars are less susceptible to the ground plane reflections, owing to their extremely narrow beams. However, the ground plane effects become significant for 2D radar systems and fixed radio links and hence must be taken into account. Figures 5(a) and (b) compare $\Delta\alpha_d$ and $\Delta\beta_d$ with and without the presence of a ground plane, for the same set of parameters described earlier. These values are obtained by UTD simulations. Higher values of $\Delta\alpha_d$ and $\Delta\beta_d$ are observed if the ground plane is accounted for. This results in an even stronger Doppler deviation compared to the case where the ground plane is neglected.

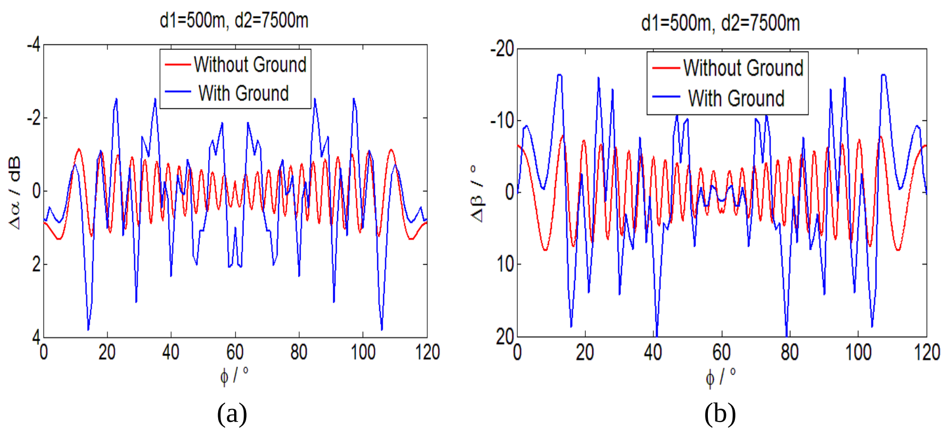

Figure 5: Impact of 3-blade rotor vs rotor angle Φ at 1.3 GHz, with and without ground plane: simulated diffraction induced (a) loss and (b) phase shift for $d_1 = 500$ m and $d_2 = 7500$ m.

4. CONCLUSIONS

One-dimensional Fresnel diffraction approach has been applied to calculate the impact of diffraction on the amplitude and phase of the WT forward scattered signal. Furthermore, deviation of the Doppler spectrum caused by the time variant amplitude and phase modulation of the two-way signal is presented. A joint time-frequency analysis of the diffracted signal has been performed using STFT to highlight the motion dynamic Doppler features. It has been demonstrated that a Doppler deviation of up to 55 Hz will occur in the forward scatter region for radars operating at 1.3 GHz. For the characterization of the WT forward scatter in the presence of a ground plane, a thorough investigation needs to be carried out by placing the WT at different locations along the radio link. Different transmitter and receiver orientations for varying antenna height and signal path also need to be considered for outlining the worst case scenario of WT interference. Moreover, the impact of multiple wind turbines has to be further investigated. An extension of the presented study has to be investigated.

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