A Signal Model of Wind Turbine Blade Based on Linear Frequency Modulation Signal and Analysis

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Abstract. Aiming at the interference problem of wind turbine blade to air tube radar, this paper proposes a wind turbine blade echo model based on LFM signal. The model considers the variation characteristics of wind turbine echo signals with blade rotation, establishes the relevant echo amplitude model and phase model, and discusses the electromagnetic scattering characteristics of wind turbine blades under different conditions. The characteristics of wind turbine blade echo signals in time domain, frequency domain and time-frequency domain are studied by using the proposed model. The influence of wind turbine blades on radar signal processing is analysed. Simulations demonstrate the effectiveness of the signal model.

1. Introduction
In recent years, the investment in the wind power industry has been expanding, and the cumulative installed capacity of wind power in the world has been exponentially increasing year by year [1]. With the wide-scale construction of wind farms and the increasingly large structure of wind turbines, wind farms may causes severe interferences on radar equipment such as air traffic monitoring and meteorological observation [2-5]. Air traffic control radar is an important source of information for monitoring airborne flight conditions in air traffic control systems [6]. Therefore, there is a huge contradiction between the development of wind farms and the use of air traffic control radars.

At the present stage, modeling the echo signals of wind farms and studying the electromagnetic scattering characteristics of wind turbines can provide a theoretical basis for wind turbine detection and clutter suppression. In [7], a wind turbine scattering signal model is proposed, but the scattering characteristics of wind turbine blades (WTB) are not considered. The literature [8] uses XGtd® software to simulate the wind turbine scattering characteristics, but its calculation is large and 3D modeling of the wind turbine is required first. The paper [9] proposed pulse Doppler radar model has strict qualification conditions. The paper [10] proposed model is only suitable for simple waveforms.

According to the actual engineering application of air traffic control radar, this paper proposes a wind turbine echo model based on linear frequency modulation (LFM) compression signal. The model is equivalent to a number of independent small scatters, and the blade echo model is constructed by the principle of scattering point superposition. In this paper, the characteristics of wind turbine echo signals in different domains are analyzed in detail. Finally, the influence of wind turbine echoes in signal processing is studied according to the model proposed in this paper.

2. WTB Signal Model
The LFM compression signal is a commonly used signal mode in airborne radar systems, which can resolve the contradiction between signal energy and range resolution. According to the scattering point superposition theory, the blade can be equivalent to several scattering points.
2.1. **Point scatter signal model**

Chirp compression is performed by adding frequency modulation to the transmitted long pulse and compressing the received signal by a matched filter receiver. The LFM signal is expressed as [11]

\[
s(t) = \text{rect}\left(\frac{t}{T_p}\right) \exp\left(j2\pi\left(f_c t + \frac{1}{2} k t^2\right)\right), \quad \frac{T_p}{2} < t < \frac{T_p}{2}
\]

(1)

Here, \(\text{rect}(t/T_p)\) denotes the rectangular pulse, whose pulse duration of \(T_p\). \(k\) is the frequency modulation rate and \(f_c\) is the carrier frequency.

Then the echo signal (de-carrier frequency) received by the radar can be expressed as

\[
s(\hat{t}, t_m) = \sigma \text{rect}\left(\frac{t_m}{T_a}\right) \exp\left(-\frac{j4\pi r(t)}{\lambda}\right) \text{rect}\left(\frac{\hat{r} - \frac{2r(t)}{c}}{T_p}\right) \exp\left(j4\pi k\left(\hat{r} - \frac{2r(t)}{c}\right)^2\right)
\]

(2)

Here, \(t_m = mT_p\) is slow time, \(\hat{t}\) is fast time, and \(t = \hat{t} + t_m\). \(T_a\) is the pulse repetition period. \(r(t)\) is the radial distance from any scattering point on the blade to the radar. \(\sigma\) is the RCS of the scattering point. According to the go-stop model, the distance change can be ignored in the pulse period [12],

\[
r(t) = r(t_m) + r(mT_p)
\]

(3)

According to the point scattering theory, the radar echo of a wind turbine blade can be expressed as:

\[
s_j(\hat{t}, t_m) = \sum_{n=1}^{N} \sum_{i=1}^{M} s(\hat{t}, t_m)
\]

\[
= \sum_{n=1}^{N} \sum_{i=1}^{M} \sigma_n \text{rect}\left(\frac{t_m}{T_a}\right) \exp\left(-\frac{j4\pi r_{n,i}(t_m)}{\lambda}\right) \text{rect}\left(\frac{\hat{r} - \frac{2r_{n,i}(t_m)}{c}}{T_p}\right) \exp\left(j4\pi k\left(\hat{r} - \frac{2r_{n,i}(t_m)}{c}\right)^2\right)
\]

(4)

Here, \(N\) is the number of blades, \(M\) is the number of scattering points on a single blade, and is the RCS of the \(i\)th scattering point on the \(n\)th blade, which is the distance from the \(i\)th scattering point on the \(n\)th blade to the radar.

Assuming the reference signal is \(s_{ref}(t) = \text{rect}\left(\frac{t}{T_p}\right) \exp\left(j\pi k t^2\right)\), then the signal after pulse compression filter can be expressed as

\[
s_{blade}(\hat{t}, t_m) = s_r(\hat{t}, t_m) \otimes s_{ref}(\hat{t})
\]

\[
= \sum_{n=1}^{N} \sum_{i=1}^{M} \sigma_n \text{rect}\left(\frac{t_m}{T_a}\right) \exp\left(-\frac{j4\pi r_{n,i}(t_m)}{\lambda}\right) B \sin\left(\frac{2\pi m}{k}\right)
\]

(5)

It can be seen from equation (5) that the \(\sigma_{n,i}\) of the scattering point determines the amplitude of the echo signal and \(r_{n,i}(t_m)\) determines the phase of the echo signal. Due to the rotation of the blades, the amplitude and phase of the echoes change with time and the position of the scattering points.

2.2. **Phase model**

\(r(t_m)\) determines the phase of the signal. Due to the rotation of the blade, \(r(t_m)\) the scattering points of different blades are changing at different times. Taking the center of rotation of the blade as the original center and the direction perpendicular to the plane of rotation of the blade as the \(x\)-axis, the geometric model between the blade and the radar as shown in the Fig.1 is established. Here, \(\alpha\) is the radar beam azimuth, \(\beta\) is the radar beam pitch angle, \(\theta\) is the blade rotation angle, and \(\phi\) is the angle between the radar beam and the blade axis.
Due to $l_i << R$, the distance between the radar and the scattering point of the blade can be approximated as

$$r_{n,i}(t_m) = \left( R^2 + l_i^2 - 2RL \cos \varphi(t_m) \right)^{1/2} = R - l_i \cos \varphi(t_m) \tag{6}$$

According to the spatial geometry knowledge, the angle between the radar beam and the blade axis can be expressed as [13]

$$\cos \varphi(t_m) = \frac{\sin \beta \sin \alpha \cos \theta(t_m) + \cos \beta \sin \theta(t_m)}{\sqrt{\sin^2 \beta \cos \alpha^2 + (\sin \beta \sin \alpha)^2 + \cos^2 \beta \cos^2 \theta(t_m) + \sin^2 \theta(t_m)}} \tag{7}$$

Here, $\theta(t_m) = \theta_0 + 2k \pi / N + \Omega t_m$, $\theta_0$ is the initial rotation angle of the blade, and $\Omega$ is the rotational angular velocity of the blade.

It can be seen from equation (7) that $r_{n,i}(t_m)$ is a function of $l_i$ and $t_m$. Due to the rotation of the blade, the distance from the radar is subject to a sinusoidal function change at a point on the blade.

### 3. Blade Echo Impact Analysis

#### 3.1. Time domain impact analysis

From equation (5), the time domain expression of the wind turbine blade is known. For air traffic radar, the distance resolution is generally several hundred meters, which is much larger than the blade length, and the LFM signal is insensitive to Doppler shift. When the interval $d$ between the scattering points tends to infinity, the equation (5) can be approximated as

$$s_{\text{blade}}(t, t_m) = \sum_{k=1}^{N} \sum_{n=1}^{M} \frac{B}{k} \sin c \left( B \left( \frac{2R}{c} \right) \right) \text{rect} \left( \frac{t_m}{T_o} \right) \exp \left( -j4\pi r_{n,i}(t_m) \right) \tag{8}$$

It can be seen from (8) that the $t_m$ acts on $\sin c \left( \frac{2\pi Md \cos \varphi(t_m)}{\lambda} \right)$, and the signal amplitude between different pulses is modulated by the singular function, only if the wind turbine blade is perpendicular to the radar line of sight (ROS), $\cos \varphi(t_m) = 0$, the pulse signal amplitude reaches the maximum of all pulses. This is because the coherent superposition of the echo points of each scattering point reaches a maximum value, which is called "flash effect".

It is known from equations (7) and (8) that the duration of the flash is related to the length of the blade, the wavelength, the angle, and the rotational speed of
the blade. When $\alpha=0^{\circ}$, $\beta=90^{\circ}$, the radar beam is perpendicular to the rotation plane of the blade, $\cos\phi(t_m)$ does not change with $t_m$. So the signal amplitude between the pulses is not modulated, and the flash effect disappears.

Since the wind turbine echo has a “flash effect”, the signal will be coherently superimposed when the blade is perpendicular to the ROS and the signal strength will increase. Therefore, the wind turbine blade echo may be larger than the CFAR threshold and be misjudged by the radar system, which will increase the false alarm probability of radar detection.

3.2. Frequency domain impact analysis

From equations (5) and (6), the Doppler frequency of the scattering point of the blade is

$$f_d = \frac{1}{2\pi} \frac{d\phi}{dt_m} = \frac{2\Omega_l}{\lambda} \sin\phi(t_m)$$

(9)

It can be obtained from equation (9) that the Doppler frequency of the blade scattering point is modulated by two sinusoidal functions by the rate of rotation [15]. However, $f_{d_{\text{max}}} = \frac{2\Omega_l}{\lambda}$, it can be concluded that the Doppler frequency of the blade varies between $[-f_{d_{\text{max}}}, f_{d_{\text{max}}}]$.

At the same time, from equation (8), the time domain expression of the entire blade superimposed by the scattering points is known. According to the Fourier transform, it can be known that:

$$\sin c(t) \xrightarrow{\text{FFT}} \text{rect}(f)$$

Therefore, for the blade echo signal, the frequency domain is in the form of a rectangular envelope with a rectangular envelope between $[-f_{d_{\text{max}}}, f_{d_{\text{max}}}]$, the wind turbine blade will produce a rectangular band. Assuming $\alpha=90^{\circ}$, $\beta=90^{\circ}$, $f_r = 1000$ Hz, then $f_{d_{\text{max}}} = 280$ Hz, the frequency domain characteristics of the blade echo are shown in Fig.4. The wind turbine blade echo produces a rectangular band between $[-280$ Hz, $280$ Hz].

Fig.2 Wind turbine echo spectrum  Fig.3 Wind turbine echo MTI schematic

Frequency domain filtering is a commonly used means for target separation, suppression of clutter, etc. Since the wind turbine blade echo will generate a frequency band, the wider the frequency band, the more likely it is to cover the target frequency information, and for the MTI filter, As a result, the MTI filter bank cannot completely filter the blade rotation frequency, as shown in Fig.5, so this method cannot effectively suppress the wind turbine blade clutter. This paper introduces the concept of frequency ratio:

$$\delta = \frac{2f_{d_{\text{max}}}}{f_r} = \frac{4\Omega_l}{\lambda f_r}$$

(10)

It is used to measure the proportion of the Doppler frequency generated by wind turbine blades to the pulse repetition frequency. The larger $\delta$, the wider the Doppler band produced by the blade, and when $\delta$ is large enough, it will affect the radar processing.
3.3. Time-frequency domain impact analysis

According to the above analysis, it is difficult to separate WTB in the time domain or frequency domain. However, from equation (9), the frequency of the wind turbine blade is a sinusoidal function of time, so the wind turbine echo can be studied in the time-frequency domain.

When the signal is in the time window centred on the flash, the echo signal is in the form of a sinc peak envelope, so the frequency domain during this time is in the form of a rectangular envelope of $\text{rect}(f)$, which a band is formed in the time-frequency domain. When the blade is perpendicular to the ROS and close to the radar, the frequency band range is $[0, f_{d_{\text{max}}}]$, and when the blade is perpendicular to the ROS and away from the radar, the frequency band range is $[-f_{d_{\text{max}}}, 0]$. There is also a "flash effect" in the domain. When at the non-flashing moment, the echo is mainly composed of strong electromagnetic scattering echoes caused by the scattering center points of the tip and the hub, so these moments are only caused by the tip and the hub scattering point in the micro-Doppler feature. The Doppler frequency is expressed as a sinusoidal envelope form and a zero band, respectively. Therefore, according to the above features, there is a possibility that the wind turbine clutter is separated from the target in the time-frequency domain to achieve clutter suppression.

4. Simulation and Analysis

Using the wind turbine blade signal echo model proposed in this paper, it is simulated by the parameters in Table 1. It is assumed that the signal does not take into account the loss during propagation and is not affected by the curvature of the Earth.

| Parameters          | Value | Unit   |
|---------------------|-------|--------|
| frequency           | 1     | GHz    |
| bandwidth           | 2     | MHz    |
| sampling frequency  | 4     | MHz    |
| PRF                 | 1000  | Hz     |
| Pulse time width    | $10^{-5}$ | s       |
| Number of blades    | 3     | -      |
| Nacelle height      | 100   | m      |
| Blade width         | 2     | m      |
| Blade length        | 20    | m      |
| PRM                 | 20    | r/min  |
| Distance to the radar | 10 | km     |

Fig.4 Time domain characteristics of wind turbine echo signals

(a) Two-dimensional structural
(b) One-dimensional structural
When $\alpha = 90^\circ$, $\beta = 90^\circ$, as shown in Fig.5, since the blade rotation speed is 20 r/min and observation time is 3 second, the three blades are perpendicular to the ROS six times, so the echo signal "flash" six times. At the same time, it can be seen from the Fig.4(a) that the echo of each pulse is sinc, and the signal amplitude between different pulses is also modulated by sinc. As can be seen from Fig.2, the blade echo frequencies are aggregated into a wider frequency band.

![Simulation data](image1)

![Measured data](image2)

Fig.5 Time-frequency domain characteristics of wind turbine echo signals

As shown in Fig.5, it is the result of performing STFT on the wind turbine blade echo signal. It can be seen from the figure that the time-frequency domain characteristics of wind turbine blades are composed of time-frequency domain "flash", sinusoidal envelope and zero-band. The theoretical analysis in Section 3.3 shows that time-frequency domain flash appears in the time-domain flickering moment due to the blade. Due to the limitation of STFT resolution, the micro-Doppler curve has a broadening effect. The simulation data is consistent with the characteristics of the measured data signals Fig.5(b), which proves the validity of the proposed signal model.

![Time domain](image3)
![Frequency domain](image4)
![Time-frequency domain](image5)

Fig.6 $\alpha = 0^\circ$, $\beta = 90^\circ$ features of wind turbine echo signals

![Wind turbine blade echo frequency ratio under different conditions](image6)

Fig.7 Wind turbine blade echo frequency ratio under different conditions
\( \alpha = 0^\circ, \beta = 90^\circ \), as shown in Fig.6, when the radar beam is perpendicular to the blade rotation plane, the radial velocity of the scattering point relative to the radar is zero, so there is no flash. Similarly, the blade echo Doppler frequency is 0, and its spectrum and time-frequency diagrams are shown in Fig.6(b) and (c).

Fig.7 simulates the relationship between the rotor blade speed and the echo frequency ratio in the case of pulse repetition frequencies of 1000 Hz, 1500 Hz, and 2000 Hz. It can be seen from the figure that the larger the speed of the wind turbine is, the more difficult it is to distinguish the target frequency from the frequency domain. At this time, increasing the radar pulse repetition frequency can reduce the frequency ratio of the wind turbine blade echo.

5. Conclusions
In this paper, the wind turbine echo model is proposed based on the LFM compression signal, and its signal amplitude model is constructed accordingly. According to the simulation results of the model in this paper, the amplitude of the single pulse echo signal and the amplitude of different pulse signals are modulated by sinc. When the wind turbine blade is perpendicular to the ROS, there is a "flash effect" in the time domain and the time-frequency domain, and a rectangular pulse band is generated in the frequency domain.

According to the analysis of the article, the wind turbine echo cannot be eliminated in the time domain and frequency domain, but the wind turbine echo can be distinguished in the time-frequency domain, which provides an idea for wind turbine clutter suppression.

References
[1] He Weikun, Wu Renbiao, et al. Research Status and Prospects of Impact Assessment and Interference Suppression Technology of Wind Farms on Radar Equipment[J]. Journal of Electronics & Information Technology, 2017,39(7): 1748-1758(in Chinese).
[2] Sozen, Kartal. Scatter and Doppler Effect of Wind Power Plants to Land Radars. Uksim International Conference on Modelling & Simulation. IEEE Computer Society, 2012.
[3] Sergey L, Hubbard O, Ding Z, et al. Advanced mitigating techniques to remove the effects of wind turbines and wind farms on primary surveillance radars[C].IEEE Radar Conference, 2008.
[4] Wen-Qin W. Detecting and Mitigating Wind Turbine Clutter for Airspace Radar Systems[J]. The Scientific World Journal, 2013(2013): 1-8.
[5] Wang J, Lok Y F, Hubbard O, et al. Impact of wind turbines On ATC radars and mitigation results[C].Radar Conference. IEEE, 2013.
[6] Zhang Wei, Zhang Xinggan. Air Traffic Primary Radar[M]. Defense industry press, 2015:7-10.
[7] Gallardo-Hernando, B., Munoz-Ferreras, JM, Perez-Martinez, F., Aguado-Encabo, F. Wind turbine clutter observations and theoretic validation for meteorological radar applications[J]. IET Radar Sonar Navig. 2011,5(2):111-117.
[8] Ohs R R, Skidmore G J, Bedrosian G. Modeling the effects of wind turbines on radar returns[C].Military Communications Conference. IEEE, 2010.
[9] Karabayir O, Yucedag S M, Coskun A F. Wind turbine signal modelling approach for pulse Doppler radars and applications[J]. Radar Sonar & Navigation Iet, 2015,9(3): 276-284.
[10] He Wei, Ning Qiuping, Guo Shuanghuang. Wind Turbine Radar Clutter Detection Based on Micro-Doppler Characteristics[J]. Signal Processing, 2017, 33(4): 496-504(in Chinese).
[11] Zhang Qun, Luo Ying. Radar target micro-Doppler effect[M]. Defense industry press, 2013:20-27.
[12] Hu Xuchao, Liu Jie, Tan Xiansi, Qu Zhiguo. A Multi-High Speed Moving Target Compensation Method[J]. Journal of Air Force Warning College, 2018,32,6: 402-406(in Chinese).
[13] He Weikun, Shi Yulu, Wang Xiaoliang. Simulation and Analysis of Wind Turbine Radar Echo[J]. Journal of System Simulation, 2015,27(1): 50-56(in Chinese).