Influence of the wind turbine blade model on echo's Doppler characteristics

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Abstract: Wind turbines have serious electromagnetic interference to nearby radar stations. Accurately obtaining the Doppler characteristics of wind turbine’s radar echo is the key technology and precondition to solve this problem. Based on the point scattering model of the wind turbines, the expression of the echo of the wind turbine blade scattering point model which is located at any point in the space is given, and the Doppler characteristic of the wind turbine blade echo is analysed by combining the existing integral model, which proves that the existing integral model is a special case of the scattering point model. Based on the radar resolution and Rayleigh resolution criteria, the scattering point spacing of the wind turbine blade is given. The simulation model is established according to the actual size of the wind turbines. After the analysis and comparison of the scattering point model and the integral wind turbine blade model, the simulation results of the wind turbine radar Doppler results are consistent with the theoretical analysis, which is of great significance to obtain the Doppler characteristics of the wind turbine blades.

1 Introduction
With the development of global clean energy, wind power generation is highly concerned by many countries [1, 2]. However, because of the existing wind turbines, the rotating blades will cause a periodic modulation effect on the electromagnetic waves emitted from the adjacent radar station, which is reflected by the radar echo with the Doppler frequency shift [3–6]. The existing research shows that it is an effective method to solve the electromagnetic interference of wind turbines by filtering the Doppler characteristics of the radar echo from the radar receiving side [7, 8]. Therefore, accurately obtaining the Doppler characteristics of the radar echo of the wind turbine is the key technology to solve the problem.

In order to obtain the Doppler characteristic of the radar echo of the wind turbines, the scholars at home and abroad have made a lot of research, mainly the field measurement [9, 10], the shrinkage ratio model experiment [11, 12], and the mathematical simulation [13–16] method. There are two kinds of methods involved in mathematical modelling of the wind turbine echo: one is to model the wind turbine echo based on the high-frequency approximation algorithm [16] which is used in the field of electromagnetic scattering to compute the radar cross section (RCS) of wind turbine blades; and the other is, under the far field condition, to use the approximate equivalent relation to equal the wind turbine blade to the scattering points, and then to model the echo of the scattering points [15]. Although the former modelling method is calculated by using the model of the blade without simplification, the results are more accurate, but the calculation of the RCS of wind turbine blades is very large by using the quasi-static method, while the latter’s modelling method greatly reduces the computation. However, considering the principle of the radar, this integral model obviously does not apply when the radar resolution is low.

In view of the shortcoming of the existing wind turbine echo modelling method, this study mainly considers that the scattering point echo model of wind turbine blades is constructed under the condition of the uniform scattering coefficient and uniformly distributed scattering point, and it is proved that the integral model is a special case of the scattering point model with the existing integral model. Also, the scattering point interval of the scattering point model is proposed with the radar transverse resolution and proved by simulation. This study is of great significance to the accurate acquisition of the echo Doppler characteristics of wind turbines.

2 Wind turbine blade echo model
The coordinate system of wind turbines and the radar position relation are established by using the gravity point of the wind turbine blade as the o and the direction perpendicular to the rotating surface of the blade as the x-axis (see Fig. 1).

Among them, the azimuth and pitch of the radar are α and β, respectively, and the angle between the blade and the radar is φ; the angle between the blade and the y-axis is θ and the initial angle is θ₀; the distance between the radar and the coordinate origin is R₀; the distance from any point Pᵢ to the radar is Rᵢ, and the distance from the origin of the coordinates is l; the rotation frequency of the blade is \( f_{rot} \).

2.1 Wind turbine blade echo scattering point model
When the radar emits a signal with a wavelength \( \lambda \), the baseband echo at the point \( P \) of the target can be expressed as

\[
S_P(t) = \sigma_P \exp\left[-\frac{4\pi}{\lambda} R_{P0}(t)\right]
\]

(1)

In the formula, \( \sigma_P \) represents the backscatter coefficient of point \( P \), \( S_P(t) \) represents the baseband radar echo of point \( P \).

In the triangle POB, the use of the cosine theorem can be obtained:
The cosine terms can be obtained by using the formula for the angle between two straight lines in a three-dimensional space coordinate system:

\[
R_p(t) = \left[ R_i^2 + l_p^2 - 2R_il_p \cos \varphi(t) \right]^{1/2} = R_i - l_p \cos \varphi(t)
\]  

(2)

The cosine terms can be obtained by using the formula for the angle between two straight lines in a three-dimensional space coordinate system:

\[
\cos \varphi(t) = \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta
\]  

(3)

In the formula, \( \theta(t) \) denotes the angle between the wind turbine blades and the y-axis at time \( t \), i.e. \( \theta(t) = \theta_i + 2\pi f_{rad} t \).

Therefore, the radar echo at point \( P \) can be expressed as

\[
S_p(t) = \sigma_p \exp \left( -\frac{4\pi R_i}{\lambda} \right) \exp \left( \frac{4\pi l_p}{\lambda} \right) \times \left\{ \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right\}^N
\]  

(4)

Assuming that a single wind turbine blade is made up of \( K \) scattering points, the radar echoes for a single blade are as follows:

\[
S_p(t) = \exp \left( -\frac{4\pi R_i}{\lambda} \right) \sum_{i=1}^{K} \sigma_i \exp \left( \frac{4\pi l_p}{\lambda} \right) \times \left\{ \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right\}^N
\]  

(5)

2.2 Wind turbine blade echo integral model

It can be seen from [15] that the carrier term and the constant phase term are removed and the echo signal at point \( P \) is as follows:

\[
S_p(t) = \exp \left( \frac{4\pi l_p \cos \varphi(t)}{\lambda} \right)
\]  

(6)

In a single leaf length \( L \) on the type of integration, available for the entire blade echo signal,

\[
S(t) = \int_0^L \exp \left( \frac{4\pi l_p \cos \varphi(t)}{\lambda} \right) \, dl_i
\]

\[
= L \cdot \exp \left( \frac{2\pi L \cos \varphi(t)}{\lambda} \right) \cdot \sin \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right) S
\]  

(7)

Bringing (3) into (7) results in:

\[
S(t) = L \cdot \exp \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right) \cdot \sin \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right)
\]

\[
= L \cdot \exp \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right) \cdot \sin \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right)
\]

(8)

Adding the scattering coefficient, carrier term, and constant phase term gives the expression of the wind turbine blade echo:

\[
S(t) = \alpha \exp \left( -\frac{4\pi R_i}{\lambda} \right)
\]

\[
\times \exp \left( \frac{2\pi l_p}{\lambda} \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right)
\]

\[
\times \exp \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right) \cdot \sin \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right)
\]  

(9)

2.3 Comparative analysis of two models

For the scattering point model, based on formula (5), the radar echo of the wind turbine blades is mainly determined by the scattering coefficients of the scattering points and the division of the scattering points on the blades. Since the scattering coefficients of the scattering points do not affect the Doppler characteristics of the blade echoes, in order to facilitate the analysis, the scattering coefficients are the same and the distribution of scatter points is studied concretely.

Let \( \sigma_p = \sigma_i = \cdots = \sigma_{pK} = \sigma \), the distance between the two adjacent scattering points is \( d \), and it can be expressed as \( d = L/(K-1) \); the distance from the scattering point \( P_i \) to the wind turbine blade gravity \( l_i = (i-1)d \). At this point, the echo of a single leaf can be expressed as

\[
S(t) = \exp \left( -\frac{4\pi R_i}{\lambda} \right) \sum_{i=1}^{K} \exp \left( \frac{4\pi (i-1)d}{\lambda} \right) \times \left\{ \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right\}^N
\]

\[\times \left\{ \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right\}^N
\]

\[\times \sin \left( \frac{2\pi l_p}{\lambda} \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right)
\]

(10)

When the interval \( d \) approaches 0 infinitely, the above equation can be transformed into

\[
S(t) = \exp \left( -\frac{4\pi R_i}{\lambda} \right) \times \exp \left( \frac{2\pi l_p}{\lambda} \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right)
\]

\[\times \exp \left( \frac{2\pi l_p}{\lambda} \cos \theta(t) \sin \beta + \sin \theta(t) \cos \beta \right)
\]

(11)

\[\times \exp \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right) \cdot \sin \left( \frac{2\pi \cos \varphi(t)}{\lambda} \right)
\]

Contrasting (9) and (11), it shows that the expression is basically the same except that the amplitude of the echo is quite different. The difference of amplitude is mainly due to the fact that (11) ignores the interval of scattering points when the integral is obtained. Since the echo amplitude does not affect the study of Doppler characteristics, the integral model of the blade is a special case of the scattering point model.

3 Wind turbine blade echo of the scattering point model

It can be seen from the above analysis that the integral model is a special case of the scattering point model. In addition, the scattering point model is closer to the real radar echo of the wind turbine blade. Therefore, the value of the scattering point interval is directly related to the accuracy of wind turbine radar echo simulation. The following will mainly analyse the problem of radar resolution wind the turbine blade scattering point model and the scattering point interval value.

The establishment of the wind turbine blade radar echo model is closely related to the radar resolution, as shown in Fig. 2. When the electromagnetic waves radiated by the radar are impinging on the blades of the wind turbine, the scattering area of the blades of the wind turbine can be regarded as many small consisted resolution units. When the radar resolution is too large, this small resolution unit can be considered as a number of scattering points. When the distance between adjacent scatterers is less than the resolution of the radar, the radar cannot distinguish the echoes of the resolving unit, so the radar echo of these unidentifiable scattering point groups can be considered as one diffuse reflection. Therefore, the integral model is used to get the difference between the radar echo of the wind turbine blade and the real target radar echo. It is very
\[
\Delta x = \left| P_1 - P_2 \right| \geq \frac{\lambda}{\cos(\Delta \theta) \sin \alpha + \sin(\Delta \theta) \cos \beta}
\]

From the above formula, the following formula can be drawn:

\[
\Delta x \geq \frac{\lambda}{2\sqrt{(\sin \alpha)^2 + (\cos \beta)^2}}
\]

Based on this, we can see that when the scattering point model is used to simulate wind turbine radar echoes, it is suggested that the scattering interval should be greater than or equal to \(\lambda / \sqrt{(\sin \alpha)^2 + (\cos \beta)^2}\) under the premise of considering the horizontal resolution of radar. In order to avoid scattering points too sparse of the wind turbine blades, the entire wind turbine echo simulation is distorted. Here, the scattering point interval takes the minimum value \(\lambda / \sqrt{(\sin \alpha)^2 + (\cos \beta)^2}\) of the above formula result.

### 4 Example simulation and analysis

Based on the above theoretical analysis, the blade model is established based on the actual size of the wind turbine 'Enercon E-66'. Among them, the length of the wind turbine blade \(L = 26\) m, the number of blades is 3, the rotation speed \(\omega = 20\) r/min, and the angle of the blade and the \(y\)-axis initial is \(90^\circ\). The distance between the radar and wind turbine blade axes \(R = 1000\) m; both the angles of the radar azimuth and pitch are met: \(\alpha = \beta = 90^\circ\). The radar signal is a single-pulse signal, the frequency of which is \(f = 1\) GHz; the pulse width is 1 \(\mu\) s, the pulse repetition frequency (PRF) is equal to \(1000\) Hz, in order to facilitate the analysis of the wind power radar echo time-frequency domain map, the simulation time is set to 3 s, i.e. a blade rotation cycle.

From the analysis of Section 2.3, we can see that when the scattering point spacing approaches 0, the scattering point model equivalent to the integral model. Therefore, here takes the scattering point interval as \(d = 0.001\) m, using the scattering point model echo simulation results shown in Fig. 3. The simulation result of the integral algorithm is shown in Fig. 4.

As can be seen from the comparison of Figs. 3 and 4, when the scattering point interval approaches 0, it can be seen that the results of the wind turbine echo is in the time domain and the time-frequency domain of the two models are very closed and can be considered as approximately equivalent, the simulation results are in good agreement with the theoretical analysis in Section 2.3. Taking integral model as an example, the time domain and time-frequency domain simulation results of wind turbine echo are analysed.

For the time-domain simulation results, \(t = (0.25 + 0.5a)\) s \((a = 0, 1, \ldots)\) for \(t = (0.25 + 0.5a)\) s \((a = 0, 1, \ldots)\) for (cos \(\theta\), + 2\(\pi f_{\text{rot}}\)) = 0. In this case, the amplitude of (11) is a peak value, and thus a time-domain peak phenomenon occurs. For the time-frequency domain simulation results, it can be seen from the figure that the Doppler characteristic curve is formed by the sinusoidal envelope curve, zero-frequency band, and the flicker in the time-frequency domain. Among them, the formation of the sinusoidal envelope curve is caused by the tip of the wind turbine blade scattering point, due to the rotation of the blade cycle, the sinusoidal envelope curve of the cycle and blade rotation cycle; zero band mainly determined by the wind turbine blade gravity and its nearby scattering point. Since this part of scattering points do not move relative to radar's position, the Doppler shift of this part of the sinusoidal envelope curve, zero band, and the flicker in the time-frequency domain appear at the moment of the peak of the field. The blades of the wind turbine and the radar are perpendicular to the line of sight at this moment, and the specular reflection and the energy of the echo provided by blades is very large, thus resulting in a flicker phenomenon.

The radar resolution suggests scattering point model blade waveform shown in Fig. 5.
5 Conclusion

In this study, aiming at the problem of the radar echo simulation of the wind turbine blade, a scattering point model is proposed based on the point scattering model, and the existing integral model is analysed theoretically. For the scattering point model, the characteristics of time-domain and time-frequency Doppler echo are analysed, and the theoretical support for the value of scattering point interval is provided in combination with the horizontal resolution of the radar. According to the actual wind turbine size simulation analysis, the simulation results show that:

(i) The Doppler characteristics of the wind turbine blade radar echo are related to the model method of wind turbine blades, and the echo Doppler characteristics obtained by different scattering point intervals are different.
(ii) The existing wind turbine blade echo integral model is a special case of the scattering point model.
(iii) When using the scattering point model to model the wind turbine blade echo, it is recommended that the scattering point interval be equal to $s(2\sqrt{(\sin\alpha)^2 + (\cos\beta)^2})$.

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7 References

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