Solution of wind turbine blade Doppler and its characteristic analysis

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Abstract: The Doppler effect caused by the dynamic rotation of the wind turbine blades is an important evidence for the identification of the wind farm clutter at the nearby radar stations. Due to the difficulty in obtaining the accurate radar echo signal of wind turbine blades by the existing methods, the accurate Doppler spectrum cannot be obtained. For that reason, the problem of accurate simulation of radar echo for wind turbine blades is avoided, and a new idea is proposed to solve the Doppler spectrum by using the dynamic radar cross section (RCS) of the blade through the study of the mechanism of the Doppler effect. Based on the matured dynamic RCS exact solution techniques of electrically large size targets, the time-domain RCS curve of blades in the dynamic motion state is obtained with the quasi-static method, using the hybrid algorithm of physical optics (PO) method and of equivalent currents method. Based on this method, calculation and analysis of the wind turbine blades’ Doppler characteristics in the rotation, torque conditions provide a reference for the recognition of radar target signal of the wind turbine, the reduction of RCS, and wind farm clutter suppression of the nearby radars.

1 Introduction

Increase of wind farms will inevitably produce more and more electromagnetic interference problems. At present, domestic and foreign scholars have searched for interference suppression technology on both sides of wind turbines and radars [1–6]. On the wind turbine side, the interference is reduced mainly by reducing the radar cross section (RCS) of the wind turbine, but the method is less effective in practical application. On the radar side, the interference suppression methods mainly use the wind turbine radar echo signal to carry out the iconic target recognition of the wind turbine blade Doppler effect, so as to filter out the winds in the wind turbine clutter components to reduce the interference. However, the actual wind turbine blades are in a rotating state, which will scatter the radar echoes with the Doppler effect to the external space [6], resulting in the difficulty in suppressing the wind turbine noise on the radar side. Therefore, the identification and analysis of Doppler characteristics of wind turbine blades is the basis of the wind turbine’s radar signal protection [7].

It is obvious that if the radar echo of the wind turbine is obtained, blade Doppler characteristic can also be obtained by using the short-time Fourier transform (STFT) [8]. The existing methods for obtaining the echo of the wind turbine involve nothing more than two models: the scaled model experiment and the simulation calculation. Although the scaled model [8–10] can be used to analyse the Doppler effect of the blade more directly, the method has a large measurement error and is not universal. In view of the simulation of the echo of the wind turbine, the point scattering model based on the wind turbine blade is proposed in the literature [11–13], but the model is obviously too rough; at present, it is only used for the qualitative analysis of the Doppler characteristic [14]. At the same time, the current study only considered the rotating motion of the blades, but lack of the actual motion of the wind turbine blades, such as torque and other movements [15–17].

Wind turbine RCS technology has been very mature; so, accurate blade dynamic RCS time series can be obtained based on the quasi-static method [18]. In this paper, because it is difficult to obtain the accurate echo of wind turbine blades and the current situation of the precise Doppler characteristics of blades, a method of solving the Doppler frequency of wind turbine echo from the dynamic RCS of the blades is proposed to realize the Doppler characteristic analysis of the blade under various motion postures, which is based on the mechanism of blades’ echo Doppler phenomenon.

2 Interference of wind turbine blades to radar and its Doppler characteristics

2.1 Interference of wind turbine blades to radar and its manifestation

The wind turbine is mainly composed of stationary tower, cabin and dynamic rotating blades. When the radar beam is exposed to the wind turbine, the radar signal will produce a certain attenuation or false target misjudgement due to the occlusion and reflection of the wind turbine. Special attention is paid to the influence between wind turbine blades and radar echo [6]. This will make the wind turbine clutter spread to a number of non-zero frequency Doppler radar filter sides, resulting in the shielding effect of radar target near the wind turbine clutter unit, and then a great increase in the false alarm rate in clutter units, which caused the interference of wind turbine blades to radar signal [8]. Judging from the current research, the key of wind turbine to radar signal interference protection is the identification and analysis of Doppler characteristics of wind turbine blades [9].

2.2 Difficulty and thought of obtaining Doppler characteristic of wind turbine blade

Due to the complexity of the structure of the wind turbine blades and the dynamic rotation of the wind turbine blades, the relative position and attitude of blades to the radar are changed in the real time. Therefore, it is difficult to describe the electromagnetic scattering characteristics of blades under the real-time dynamic rotation by a simple point scattering model which makes it difficult to accurately identify and analyse the Doppler characteristics caused by blade rotation directly from the wind turbine radar echo.

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Therefore, the technical problems of getting wind turbines echo accurately is bypassed and it is found that the Doppler characteristics of the wind turbine echo can be obtained by blade dynamic RCS through the analysis of the mechanism of the Doppler effect caused by the radar echo of the wind turbine rotor and the close correlation between the radar signal and the dynamic RCS of the wind turbine. Due to the fact that the current method for solving wind turbine RCS is very mature, dynamic RCS of wind turbine blades can be obtained under on the fact that blades fully meet the requirements of the quasi-static method, which can be used to achieve the accurate analysis of blade radar echo Doppler characteristics of the wind turbine.

3 Solution of Doppler frequency of blade based on dynamic RCS

3.1 Relationship between dynamic RCS and Doppler effect

Assuming that the radar incident electromagnetic wave direction is \( i \), the velocity vectors of a surface element of wind turbine blades’ surface is \( v \), in a time of \( t_1 \), a wavefront of the electromagnetic wave meet with \( \Delta S \) and reflection occurs at this time, the distance between the next wavefront and \( \Delta S \) is an electromagnetic wavelength \( \lambda \), as shown in Fig. 1a. After the time interval \( \Delta t \) to time \( t_2 \), the next wavefront will meet with \( \Delta S \) and reflect as shown in Fig. 1b. The time interval \( \Delta t \) is

\[
\Delta t = \frac{\lambda}{c + v \cdot i}
\]

where \( c \) is the speed of light.

Thus, the wavelength \( \lambda' \) of the radar echo at time \( t_2 \) is

\[
\lambda' = ct - (v \cdot i)t
\]

According to formulae (1) and (2), the frequency of radar echo can be obtained as follows:

\[
f' = \frac{c}{\lambda'} = f' \frac{c + v \cdot i}{c - v \cdot i}
\]

So, the Doppler frequency \( f_d \) is

\[
f_d = f' - f = f \frac{2v \cdot i}{c - v \cdot i}
\]

When \( v \ll c \), it can be assumed that

\[
f_d \simeq f \frac{2i \cdot v}{c}
\]

In fact, the moving speed of each element of the wind turbine blade is completely up to \( v \ll c \).

At any given time and angle, the RCS of any \( \Delta S \) surface element of the wind turbine blade can be expressed as [19] follows:

\[
\sigma = a \exp \left[ i(\alpha_0 + 2kvt \cdot i) \right]
\]

where \( \sigma \) is the RCS of the surface element, \( a \) is the amplitude of the surface element RCS, and \( \alpha_0 \) is the initial phase of the surface element.

Assuming that the surface element \( \Delta S \) is at the speed of \( v \) translation and no rotation, then after the time \( t \), the position of \( \Delta S \) is \( r(t) \).

Assuming that \( \Delta S \) is still here (i.e. quasi-static), its RCS is

\[
\sigma = a \exp \left[ i(\alpha_0 + 2kvt \cdot i) \right]
\]

where \( k \) is the free space wave number, \( k = 2\pi/c \).

Formula (7) is regarded as a simple harmonic vibration:

\[
\sigma(t) = a \exp \left[ i(\alpha_0 + 2\pi f_d t) \right]
\]

The vibration frequency is

\[
f_d = \frac{k}{\sigma} \cdot \frac{2\pi i \cdot v}{\lambda} = f \frac{2i \cdot v}{c}
\]

Obviously, the frequency is exactly the Doppler frequency of the wind turbine blade radar echo shown in (5), that is, the fluctuation frequency of the RCS of the linearly moving blade \( \Delta S \) with time is in line with the Doppler frequency of the radar echo produced by the \( \Delta S \) movement.

Note that the actual rotating speed of the wind power generator is usually 12–24 RPM [20]; therefore, in a very small time interval, in addition to the part that is close to the centre of rotation of the blade, each facet on the blade can be regarded as the translation. However, the velocity and direction of the plane are different, so that the radar echo Doppler frequency will occupy a certain width of the frequency band. Based on this, if the dynamic RCS of the blade can be obtained, the fluctuation frequency of the dynamic RCS of the blade can be solved by the mathematical transformation method; that is, the Doppler frequency of the blade radar echo, so that Doppler characteristics of the wind turbine blades of radar echo can be analysed.

3.2 Acquisition of blade dynamic RCS

At present, there is no report on the study of the dynamic RCS of blade, but the static RCS of blade can be solved by the PO-equivalent currents method (ECM) hybrid method [21]. However, due to the complex shape of the rotor blades and the real-time rotation, it is difficult to obtain the analytical expression of the dynamic RCS of the blade by varying the time [12]. For the echo simulation problem of ballistic micro-motion targets, a quasi-static method is used to approximate the scattering field of a moving object at a moment using the scattering field of the target that is still at the point in the literature [18]. The ‘quasi-static method’ requires that the rotational frequency of the moving object is much smaller than the frequency of the incident electromagnetic wave. The maximum linear velocity on the object is much smaller than the speed of light, and the actual rotating wind turbine blade satisfies this condition.

Therefore, the quasi-static method is used to obtain the dynamic RCS based on the PO-ECM hybrid method to solve the blade static RCS.

3.3 Solution of blade Doppler frequency

Although the dynamic RCS of the blade can be obtained by the aforementioned quasi-static method, the dynamic RCS is discrete and discontinuous, and the Doppler frequency of the blade radar

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The method requires the time series of dynamic RCS to be sampled firstly. According to the Nyquist sampling theorem [22], the sampling frequency RCS of the blade f_s needs to be satisfied:

\[ f_s > 2f_{\text{max}} \]  

(10)

where \( f_{\text{max}} \) is the maximum Doppler frequency caused by the rotation of the blade, \( f_{\text{max}} = 2\pi R\omega / c \), \( \omega \) is the rotation speed of the blade, and \( R \) is the length of the blade.

When the sampling frequency \( f_s \) is determined, the corresponding rotation angle of the corresponding sample is

\[ \delta = \omega f_s \]  

(11)

After determining the sampling interval of the dynamic RCS, the dynamic RCS signal is determined. Let \( x(k) \) be the discrete RCS signal of the blade obtained by sampling, in [23], then the discrete form of the \( x(k) \) signal is

\[ S_p(t, f)_{\text{res} \Delta f = v/c N} = S_p(m, n) = \sum_{k=0}^{N-1} x(k\Delta t)w((k\Delta t - m\Delta t)e^{-j2\pi n/m}) \]  

(12)

where \( N \) is the total number of sampling points; \( k, m, n = 0, 1, 2, 3...N-1; \Delta t \) is the sampling interval of time variables; \( w(t) \) is a window function with a short time window, and \( * \) represents the complex conjugate.

From formula (12), the transformation result is a two-dimensional complex matrix, whose elements correspond to the amplitude of the RCS spectrum of the blade, the rows correspond to the RCS sampling time of the blade, the columns correspond to the RCS frequency of the blade, namely the radar echo Doppler frequency value of the blade.

In conclusion, based on the equivalence relation between the dynamic RCS fluctuation frequency and the Doppler frequency of the blade radar echo, we can use the quasi-static method, sampling theorem, PO-ECM mixing method, STFT, and finally solve the wind turbine Doppler frequency of the blade on the surface is close to the vertical irradiation. The contribution of the physical optical RCS on the surface increases; so, the rear row of RCS increases. For the same reason, forward blades’ RCS should also be increased, but the increase relative to the original RCS is too small.

5 Conclusion

(i) According to the relationship between the dynamic RCS of the wind turbine blade and the Doppler characteristic of the radar echo, the Doppler frequency of the blade radar echo signal can be obtained indirectly by solving the fluctuation frequency of the dynamic RCS of the wind turbine blade.

(ii) The characteristics of the Doppler spectrum of the wind turbine blades are more obvious than those of the RCS blade at a certain time interval, and then the dynamic RCS of the blade is obtained by connecting these calculated discrete RCSs (including amplitude and phase).

The RCS and its Doppler frequency of the wind turbine blades are controlled by 4 GHz, horizontally, vertically polarised electromagnetic wave, wind turbine blades in the motion postures such as rotation and torque, as shown in Figs. 3 and 4.

According to the motion characteristics of wind turbines under typical wind conditions [15], the total torque of 7° is applied to the wind turbine blades, that is, the 7° angle of attack of the blades, the RCS curve and the Doppler spectrum of the simulation are shown in Figs. 3b and 4b. Comparing Fig. 3b with Fig. 3a, it is difficult to see the effect of the applied total moment on the RCS of the wind turbine blade from the RCS dynamic curve with or without the total moment. However, the Doppler spectrum comparison shows a significant difference: the amplitude of the negative portion of the Doppler frequency increases, and the change in the case of vertical polarisation is more pronounced, where vertical and horizontal polarisation under the average increase rate are 0.0141 and 0.0089 m², respectively.

The negative part of the frequency comes from the contribution of the posterior blade, that is, the electromagnetic wave illuminates the blade from the trailing edge. When the blade angle is increased from 0° to 7°, the windward area of the blade increases, and the surface of the blade is closer to the vertical irradiation. The contribution of the physical optical RCS on the surface increases; so, the rear row of RCS increases. For the same reason, forward blades’ RCS should also be increased, but the increase relative to the original RCS is too small.

Fig. 2 Geometry model of wind turbine blades RCS
curve in the time domain, and also contain some information that cannot be obtained by the RCS curve in the time domain.

(iii) According to the Doppler spectrum characteristics of wind turbine blades in the motion, such as rotation, torque, it can provide a reference for wind turbine target identification for radar stations, and provide a theoretical basis for the follow-up of wind farm clutter suppression, feature extraction and wave RCS reduction method.

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7 References

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