



Wind Turbine Clutter Suppression for Weather Radar Using Improved Ridge Regression Approach

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Abstract. The problem of clutter suppression is gaining importance because of many disadvantages. However, conventional clutter suppression methods cannot eliminate the great disturbances to radar system caused by wind turbines. An improved ridge regression algorithm is investigated to accurately estimate the spectral moment of the weather signal contaminated by wind turbine clutter (WTC) in this paper. Firstly, a weighted regression model is introduced to solve the problem that the strong collinearity of the data in the regression model leads to unstable parameter estimation. Then the optimal regression parameter in the model is obtained by generalized cross validation (GCV) to improve the estimation accuracy of weather signal. Theoretical analysis and simulation results show that the spectral moment recovered by the proposed algorithm has better accuracy and stability in lower SNR.

Keywords: Weather radar · Ridge regression · Clutter suppression

1 Introduction

In recent years, the clutter suppression technology of wind turbine by weather radar has been widely concerned by more and more countries. By using simulation and measured data, scientists from various countries have analyzed the distribution characteristics of clutter and weather echo of wind turbine under different working modes of weather radar both in the time-domain and frequency-domain in detail. Accordingly, different suppression algorithms are proposed as followings: the adaptive spectrum processing algorithm proposed by Kong [1]; the range-doppler regression (RDR) algorithm proposed by Nail [2], the turbine clutter suppression method based on the adaptive filter (such as Wiener filter, etc.) proposed by Yan [3], and the signal separation method proposed by Frank [4]. Regression algorithm is widely used in clutter suppression for the simple model and high operational efficiency. However, due to the limitations of wind farm scale, fan speed, weather radar working mode and other practical conditions, the above algorithm cannot take into account clutter suppression of wind turbines and lossless recovery of weather information.

In view of the above problems, in this paper, based on the RDR algorithm, an improved ridge regression algorithm is studied. By introducing the weighted regression

model, and selecting generalized cross validation (GCV) in solving the optimal regression parameter achieve the effect of optimizing the solving process. Moreover, the calculated ridge regression coefficient for the collinearity and stronger robustness is ensured, and the high precision of the recover of contaminated weather echo signal information is realized.

2 Weather Radar Signal Model

Assuming that the wind turbine clutter(WTC) signal is received by the i^{th} range bin of the weather radar, and the received signal under the k^{th} pulse is [5]:

$$C_i(k) = s_i(k) + w_i(k) + n_i(k), k = 1, \dots, K \tag{1}$$

where K is the pulse number, $s_i(k)$ is the weather signal, $w_i(k)$ is the wind turbine clutter, $n_i(k)$ denotes the noise.

Adjacent range bins do not contain WTC signals, and the received signal under the k^{th} pulse is:

$$C_j(k) = s_j(k) + n_j(k), k = 1, \dots, K \tag{2}$$

The dynamic clutter caused by the high-speed rotation of the blades of wind turbines has a wide doppler spectrum, so WTC and weather targets will produce serious overlap in time and frequency domains, that is, the weather signal will be submerged in the clutter of wind turbines, and the spectral moment information of the weather signal of the polluted range bin will be seriously disturbed.

3 Improved Ridge Regression Approach

3.1 The Principle of Ridge Regression

Ridge regression is an improved method of least square estimation. Regularization is carried out on the original regression model and the solution process was optimized by adding penalty term. The general regression model is defined as follows:

$$Y = X\beta \tag{3}$$

where Y is the real values of spectral moment parameters, β is the regression coefficient to be found, and X is a fitting matrix defined as:

$$X = \begin{bmatrix} 1 & r_{i-10} & r_{i-10}^2 \\ \dots & \dots & \dots \\ 1 & r_{i-1} & r_{i-1}^2 \\ 1 & r_{i+1} & r_{i+1}^2 \\ \dots & \dots & \dots \\ 1 & r_{i+10} & r_{i+10}^2 \end{bmatrix}_{20 \times 3} \tag{4}$$

where r_i is the slant distance size of scattered points of the i^{th} range bin, the dimension of $X_{L \times M}$ is $L \times M$. L is the amount of selected units which is defined as $L = 20$, that is to take 10 range bins on both sides of the i^{th} range bin with WTC contamination, and M is the degree of polynomial which is defined as $M = 3$.

A fitting estimation matrix including distance units contaminated by WTC is denoted as X^* :

$$X^* = \begin{bmatrix} 1 & r_{i-10} & r_{i-10}^2 \\ \dots & \dots & \dots \\ 1 & r_{i-1} & r_{i-1}^2 \\ 1 & r_i & r_i^2 \\ 1 & r_{i+1} & r_{i+1}^2 \\ \dots & \dots & \dots \\ 1 & r_{i+10} & r_{i+10}^2 \end{bmatrix}_{21 \times 3} \quad (5)$$

Ridge regression cost function is given by:

$$\min \left\{ \|X\beta - Y\|^2 + k_{ridge} \|\beta\|^2 \right\} \quad (6)$$

where k_{ridge} is ridge regression parameter. Ridge regression coefficient is solved as follows:

$$\beta = (X^T X + k_{ridge} I)^{-1} X^T Y \quad (7)$$

The estimated value of the corresponding parameter Y is given by:

$$\tilde{Y} = X^* \cdot \beta = X (X^T X + k_{ridge} I)^{-1} X^T Y \quad (8)$$

The algorithm uses the weather information of unpolluted range bins, introduces an improved ridge regression algorithm, and then estimates the average doppler velocity, velocity spectrum width, power and other effective information of weather signals in the polluted range bin through efficient fitting.

3.2 Weather Information Extraction

The average doppler velocity of the echo signal is estimated as follows [6]:

$$V = \left(\frac{\lambda}{4\pi/PRF} \right) \angle R_{01} \quad (9)$$

The average spectral width is estimated as:

$$\sigma = \frac{\lambda}{2\sqrt{2}\pi/PRF} \left| \ln \frac{R_{01}}{|R_{11}|} \right|^{1/2} \quad (10)$$

The average power is estimated as:

$$p = R_{0l} \tag{11}$$

where R_{0l} Represents zero delay auto-correlation parameter of echo signal sequence of the l^{th} unit to be processed, and R_{1l} represents the first order auto-correlation parameter of the echo signal sequence of the l^{th} range bin. Ultimately the estimated spectral moment parameters of the weather signal in the unit polluted by WTC can be obtained as V_{est} , σ_{est} and p_{est} .

3.3 Improved Ridge Regression

An improved ridge regression uses the weighted regression model, and solves the optimal regression parameter by introducing GCV. Suppose the singular value decomposition of the X in the regression model is:

$$X = UDV \tag{12}$$

where U is a positive definite matrix of order L , and V is that of M . The dimension of D is $L \times M$, the diagonal element of which is the square root of the eigenvalue λ_n ($n = 1, 2, \dots, M$) of $X^T X$. Define $M(k_{ridge}) = X(X^T W X + k_{ridge} I)^{-1} X^T W Y$, where W is the fitting weight corresponding to each range bin. The fitting weight of the j^{th} range bin nearby is:

$$W_j = \begin{cases} \frac{1}{2} [1 + \cos((\pi/L_{prox})|j - i|)], & 0 \leq |j - i| \leq L_{prox} \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

where L_{prox} is the distance threshold, and $L_{prox} = 10$.

The validation function of generalized cross validation is as follows:

$$GCV(k_{ridge}) = \frac{L^{-1} \|Y - \tilde{Y}\|^2}{[1 - L^{-1} \text{tr}(M)]^2} \tag{14}$$

which can be simplified as:

$$GCV(k_{ridge}) = \frac{L^{-1} \sum_{i=1}^L (k + \gamma_i)^{-2} \bar{y}_i^2}{[L^{-1} \sum_{i=1}^M (k + \gamma_i)^{-1}]^2} \tag{15}$$

where $U^T Y = (\bar{y}_1, \bar{y}_2, \dots, \bar{y}_L)$, and γ_n is defined by:

$$\gamma_n = \begin{cases} \lambda_i, & i = 1, 2, \dots, M \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

The obtained optimal ridge regression parameter k_{ridge}^* is substituted into the improved ridge regression model, and the estimated values of spectral moment parameters of the weather signal in the range bin polluted by WTC are input to obtain the fitting values of spectral moment parameters of meteorological signals in the range bin polluted by WTC, which contains v_{ridge} , σ_{ridge} and p_{ridge} .

4 Simulation Results and Performance Analyses

The validity of the proposed algorithm is verified by computer simulation. The main simulation parameters of the radar system are listed in Table 1.

Table 1. Simulation parameters.

Parameters	Values
Carrier frequency f_0	5.5 GHz
Pulse repetition frequency	1000 Hz
Radar height	1000 m
Wind turbine height	880 m
Wind turbine rotate speed	15 r/min
Wind turbine blade length	26 m

RDR algorithm [2] proposed by Nail is selected for performance comparison in this paper. Firstly, the solution of optimal ridge regression parameters is verified. GCV is introduced into ridge regression algorithm to solve the optimal ridge regression parameter. Due to the fitting matrix of every scatter points is in contact with the weather signal model of oblique distance only, the optimal value of the ridge regression parameter given by GCV is a constant.

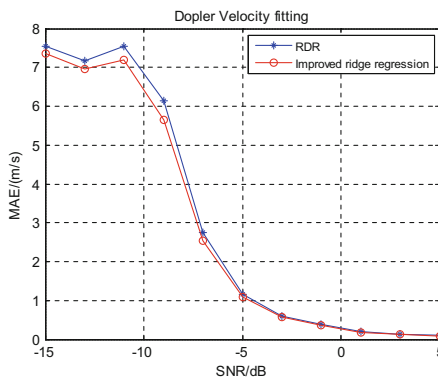


Fig. 1. Comparison of average doppler velocity fitting errors.

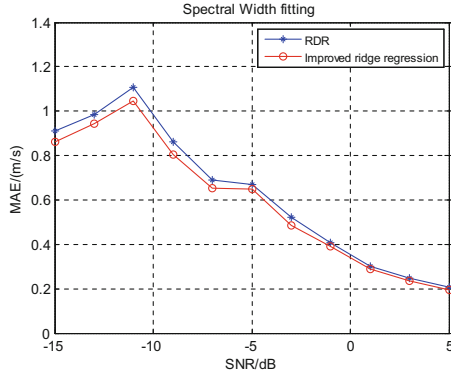


Fig. 2. Comparison of average spectral width fitting errors.

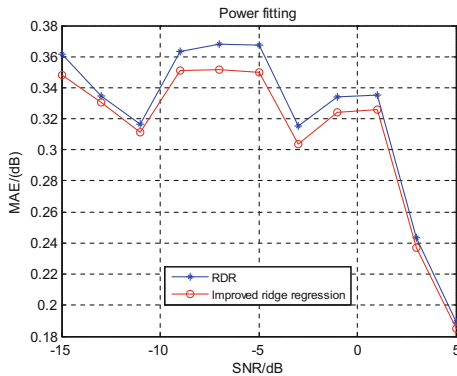


Fig. 3. Comparison of average power fitting errors.

The polynomial fitting method is adopted to estimate spectral moment of weather signals in the polluted range bin. As shown in Fig. 1, 2 and 3, when the SNR is lower than 5 dB, the fitting error of this algorithm is better than that of RDR. That is, this algorithm can still estimate spectral moment with higher accuracy under the condition of low SNR, and the recovered weather signal returns have higher accuracy, which effectively suppressing the influence of WTC on weather information.

5 Conclusion

This paper proposes the weighted ridge regression model for suppression of WTC for weather radars. GCV is introduced to solve the optimal regression parameter, and the spectral moment parameters of weather signals in the range bin polluted by WTC are fitted with high accuracy. Compared with RDR algorithm, the fitting error of the algorithm in this paper is smaller under the condition of low SNR, and the recovered spectral moment information is more accurate.

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