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Research article

Wind speed and direction measurement based on arc ultrasonic sensor array signal processing algorithm

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ABSTRACT

This article investigates a kind of method to measure the wind speed and the wind direction, which is based on arc ultrasonic sensor array and combined with array signal processing algorithm. In the proposed method, a new arc ultrasonic array structure is introduced and the array manifold is derived firstly. On this basis, the measurement of the wind speed and the wind direction is analyzed and discussed by means of the basic idea of the classic MUSIC (Multiple Signal Classification) algorithm, which achieves the measurements of the 360° wind direction with resolution of 1° and 0–60 m/s wind speed with resolution of 0.1 m/s. The implementation of the proposed method is elaborated through the theoretical derivation and corresponding discussion. Besides, the simulation experiments are presented to show the feasibility of the proposed method. The theoretical analysis and simulation results indicate that the proposed method has superiority on anti-noise performance and improves the wind measurement accuracy.

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1. Introduction

Nowdays, more and more people pay attention to the natural ecological environment and sustainable development. As a kind of green, clean and renewable energy, wind energy [1] has been widely applied in many fields such as wind water pumping [2], wind power generation [3–7] and wind navigation [8]. The accurate measurement of wind speed and direction plays an important role in these fields. For example, in the design process of wind power pumping water system, the wind speed is employed for the construction of the mathematical model [2] because the volume flow of the system pump water is a function of wind speed and the water pumping system decreases with the increasing of the wind speed [9]. The rational use of the wind energy in the ship also promotes the environmental protection and energy conservation. The accurate measurement of the wind speed and direction is vital to the reliability and security of the wind energy navaid system [10]. For the design of the wind power generator, the target area should be explored firstly. Then the range of the wind speed is determined according to the historical data of the wind speed and direction in this area and the wind turbine is selected. Meanwhile, the real time detection of the wind speed and direction is needed during the running of the wind power generator to ensure the normal operation of the system [11–14]. Besides, the measurement of the wind speed and direction also plays important roles in the areas of meteorological observation and scientific experiment [15,16].

In these applications, numerous types of wind measurement instruments have been developed, in which the commonly used instruments are mechanical anemometers [17–19], thermal anemometers [20–22], windmill anemometers [23], drag-force anemometers [24], pressure tube anemometers [25], laser Doppler anemometers [26], FBG anemometers [27], ultrasonic anemometers [28] and so on. The most commonly used mechanical anemometers are wing anemometers and cup anemometers, which utilize the propeller speed or wind cup or other functional relationship among the environmental parameters and wind speed to measure the wind speed [17–19]. The mechanical anemometer has been widely used for its simplicity. However, due to the presence of rotating parts, the mechanical anemometer has disadvantages of mechanical wear, short life, high maintenance cost, low accuracy which affect its further application. The thermal anemometer utilizes a thermal probe to measure wind speed through measuring the radiating rate of the heat element [20,21]. The main disadvantage of the thermal anemometer is its small measuring range. Nowadays, the ultrasonic wind measurement technology (UWMT) is widely employed due to its high accuracy, wide measuring range, various application occasions and many other advantages. The most widely used method in UWMT is time-difference theory [28], which utilizes the difference

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of propagation time between downwind and upwind to measure wind speed. In addition, other measuring principles applied in UWMT are phase method [29], Doppler method [30], correlation method [31] etc [32,33]. However, due to the complexity of the principles and difficult to realize, these principles are not widely used.

Array signal processing method can effectively suppress the noise existing in complex environment. It is widely employed for its advantages of more flexible wave beam control, higher gain, stronger interference suppression and higher spatial resolution [34]. However, the application of the array signal processing theory to the study of meteorological instruments is rare, especially in the field of the ultrasonic wind measurement research. In [35], a kind of wind speed and direction measurement method exploiting ultrasonic sensor array was presented, in which a special array structure was adopted. In its array structure, a sensor was located in the upper layer to transmit the ultrasonic wave while other four sensors were located in the lower layer to receive the running ultrasonic wave and the time difference method was employed as the wind measuring algorithm. However, the redundant information introduced by the array structure was not considered and the measurement accuracy entirely depended on the measurement of ultrasonic transmission time difference. In particular, in the case of strong electromagnetic interference or low signal-to-noise ratio, the time measurement of the ultrasonic transmission would become difficult or even lead to failure.

In this article, the ultrasonic sensor array structure and the array signal processing algorithm are combined and applied to wind measurement system, which can measure wind speed and wind direction accurately under low signal-to-noise ratio conditions. The theoretical analysis and simulation experiments validates that the proposed method improves the measurement range and accuracy of the wind measurement system effectively. The organization of this article is as follows. Firstly, the principle of the proposed method and the implementation process are introduced. Secondly, the key issues of array ambiguity and resolution of the proposed method are analyzed and discussed. Thirdly, the simulation experiments of the proposed method are implemented and the feasibility of the proposed method is validated. The performance of the proposed method is also illustrated. Finally, the proposed method of the article is summarized.

2. Principle

2.1. Principle overview

The traditional array signal processing method is usually supposed that the array system locates in the far field condition. Hence, the arrival signals of wavefront in the array system can be approximately regarded as plane wave. Meanwhile, the time delay of signals impinging at adjacent receiving array elements only relates to the direction of the signals. However, in the case of near field, the arrival signals are no longer plane wave, but spherical wave. In this case, the signal time delay of adjacent receiving array elements relates to not only the direction of the signal, but also the distance between the signal source and the array elements. Therefore, we propose a method based on the principle of near field array under the conditions of fixed position of transmit and receive array elements in this article. Thus, the ultrasonic sensor array output data matrix is only related to the wind speed and the wind direction, and the wind speed and wind direction information can be estimated from proposed array signal processing algorithm.

Three basic simplifications are applied to establish the mathematical model in this article. The first simplification is to consider that the travel of one pulse along the acoustic path is only affected by the local component of wind speed vector that is parallel to the acoustic path. The second simplification consists of considering a model of incompressible homogeneous and isotropic turbulence. The third simplification is to consider the validity of Taylor's hypothesis of frozen turbulence [36].

In this article, an ultrasonic sensor array with arc structure is constructed and the model of near field acoustic propagation is established. Furthermore, the array receiving signal vector matrix is analyzed. Finally, the wind speed and wind direction are estimated by proposed multiple signal classification (MUSIC) algorithm.

2.2. Mathematical model

2.2.1. Array output model

Given that a near field narrow band signal impinges on arbitrary sensor array. The sensor array number is M and all array elements are isotropic with no channel inconsistency or mutual coupling. The ultrasonic signals are received by the sensor array elements and transmitted to the processor through the respective channels. Assuming the ultrasonic transmission signal is $s(t)$, the signal received by the ith array element is

$$x_i(t) = s(t) * e^{-j2\pi f \tau_i} + n_i(t) \tag{1}$$

where $i = 1, 2, \cdots, M$, f is the frequency of transmit ultrasonic, τ_i is the time delay of transmission signal from the reference array element to the ith array element and $n_i(t)$ is the noise on the ith element of the array.

The signals received by the M array elements at t moment are expressed as a column vector:

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ \vdots \\ x_M(t) \end{bmatrix} = \begin{bmatrix} e^{-j2\pi f \tau_1} \\ e^{-j2\pi f \tau_2} \\ e^{-j2\pi f \tau_3} \\ \vdots \\ e^{-j2\pi f \tau_M} \end{bmatrix} S(t) + \begin{bmatrix} n_1(t) \\ n_2(t) \\ n_3(t) \\ \vdots \\ n_M(t) \end{bmatrix} \tag{2}$$

The Eq. (2) is further rewritten as matrix form:

$$X(t) = AS(t) + N(t) \tag{3}$$

where $X(t) = [x_1(t), x_2(t) \cdots x_{\mathrm{M}}(t)]^T$ is the array receiving signal matrix, $N(t) = [n_1(t), n_2(t), \cdots, n_{\mathrm{M}}(t)]^T$ is the noise matrix and $\boldsymbol{A}$ is the array manifold matrix, which is expressed as :

$$A = \left[e^{-j2\pi f \tau_1}, e^{-j2\pi f \tau_2}, \cdots, e^{-j2\pi f \tau_{\mathrm{M}}}\right]^T \tag{4}$$

According to the array signal processing theory, the estimated parameters are implied in the time delay $\tau_i (i = 1, 2, \cdots M)$. Furthermore, for the different array structures, the array manifold matrix (Eq. (4)) is also different. Therefore, the essence of the spatial parameter estimation issue based on array is transformed to the parameter identification problem under different array manifold conditions.

2.2.2. Delay derivation of near field ultrasonic transmission model

In this article, a kind of arc ultrasonic sensor array is designed, of which the structure is indicated in Fig. 2.1. In the figure, the sensor 0 is the transmission ultrasonic sensor and the sensor 1–5 are the receiving ultrasonic sensor array, which are uniformly arranged on the arc with sensor 0 as the circle center and R as the radius. The sensor 0∼5 are composed of the proposed wind measurement array system.

In Fig. 2.1, V is the measured wind speed; θ is the measured wind direction angle which is indicated by the coming wind relative to the vertical direction and the range of θ is $0 \sim 359^\circ$; $V_1 \sim V_5$ are the components of the wind speed V in the direction

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