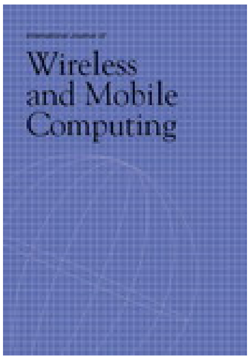


International Journal of Wireless and Mobile Computing

ISSN online: 1741-1092 - ISSN print: 1741-1084
https://www.inderscience.com/ijwmc

Low-level wind shear of wind field modelling and simulation

Zhang Ye, Jia Meng

DOI: 10.1504/IJWMC.2023.10061391

Article History:

Received:	02 November 2022
Last revised:	11 December 2022
Accepted:	11 January 2023
Published online:	07 February 2024

Low-level wind shear of wind field modelling and simulation

Zhang Ye and Jia Meng*

Xinxiang University,
Ürümqi, Xinjiang, China
Email: 12066090@qq.com
Email: jiameng@xxu.edu.cn
*Corresponding author

Abstract: Wind shear refers to a meteorological phenomenon. It happened when wind speed, wind direction separately or both simultaneously changes rapidly. If the microburst is below altitude of 300 metres, the probability of occurrence increases greatly. Three wind shear wind field modelling methods have been introduced in this paper. By use of computer numerical simulation, the model can not only simulate the real wind shear of wind field, but also provide other useful physical quantities. In the study of low-level wind shear detection system process, the wind field model that can truly reflect the physical characteristics change of wind field is established. The experiments results show that most typical shear wind field is caused by the down flow.

Keywords: low-level wind shear; wind field model; wind field profile.

Reference to this paper should be made as follows: Ye, Z. and Meng, J. (2024) 'Low-level wind shear of wind field modelling and simulation', *Int. J. Wireless and Mobile Computing*, Vol. 26, No. 1, pp.19–24.

Biographical notes: Zhang Ye worked as a teacher in Xinxiang University until now. In 2011, he received a master's degree of communication and information system in Zhengzhou University. His research interests include capacitive micro-machined ultra-sound sensor and structural health monitoring.

Jia Meng obtained a doctor's degree from Northwestern Polytechnical University, majoring in electronic science and technology. In December 2020, he was employed as a professor in Xinxiang University, and his research fields are signal processing and machine vision.

1 Instruction

Wind shear is one of the most dangerous factors when the aircraft is taking off and landing. It discussed the methods of setting up changing wind shear field model. According to NASA proposed model, it set up a simplified engineering model and conducted a computer simulation. This dissertation focused on the radar echo signal model, including wind shear echo signal model and clutter model, using the principle of Doppler frequency shifting. The proposed model should both simulate character of the micro flow and be convenient for the wind shear radar signal detection system to do simulation (Widrow et al., 1976; Widrow and Walach, 1984; Widrow, 2005; Widrow et al., 1975; Baxa, 1993; Britt and Kelly, 1990).

Micro critical flow refers to a small scale under the strong airflow. It happens when the low outgoing air emission hits the ground. In terms of low range, it is characterised by obvious down flow form. The average width of flow is a few hundred metres to several kilometres. Its life is for a few seconds to a few minutes, it spreads from the ground to all around after hitting, and twisting upwards to form a sudden wind. The extended diameter is up to 1 to 3 kilometres. The wind speed of wind head and wind tail can be up to 10 to 50 metres/s.

In the simulation of the actual wind field, a few simple characteristic values is not enough. It must contain wind field structure of the surrounding area of airport, or at least the main landing take-off runway and it should also have a relatively detailed, comprehensive and timely recognition. Only in this way can we do the detection and prediction of wind shear, which can avoid disastrous accident. In this respect, many countries especially the USA, invested a lot of manpower and material resources to do the long-term research in many aspects.

The wind shear of wind field model mainly has three categories (Widrow et al., 1975; Baa and Lai, 1993; Kunkel, 1992):

1 By the airport weather radar network and all kinds of monitoring network, the model collects the measured data by certain difference method, records the wind

speed and direction of wind field and other relevant data in the form of a grid. The characteristic of the model is that the data are true and correct. But these measured values can be scattered small, not enough to reflect the essential characteristic of low-level wind shear and dynamic development process, which does not change according to the difference of the meteorological conditions. Second, the model of data storage capacity is big, not suitable for simple analysis and the need of real-time simulation. Moreover, the wind field data acquisition depends on the advanced measuring equipment, and it costs much for manpower and financial resources.

2 The second category of wind shear wind field model is a common engineering of simple model. It generally composed by some physical concepts in the form of simple mathematical fitting and fluid mechanics basic solution stack. Its characteristic is only reflect some of the essential characteristics of shear wind field and not emphasise all capture the real wind field characteristics, which is very simple, especially suitable for the analysis of the influence of wind shear on flight characteristics and apply in the simulator training pilots (Li et al., 2016).

3 The third type of wind shear model is a description of small scale meteorological atmospheric dynamics equation and physical equation as the foundation, which is solved by large computers directly. In the USA, the TASS model presented by NASA company is the typical model in practice. TASS model is a three-dimensional time-varying convective clouds blow air under micro wind shear model, including 11 mutual coupling control equation. Among them, three momentum equation, a pressure equation and the equation 1 bits temperature. There are 6 describe the atmospheric moisture (water vapour, cloud droplets, crystal, hail, rain and snow, etc.) of the equation. In addition, the model also includes the influence of surface roughness and micro-physical process in the cloud, etc. The characteristic of the numerical wind shear wind field model is divided into three-dimensional space which must be a certain density of grid points to solve by the computer. In order to improve the resolution, it needs to provide a large number of grid point data, a large capacity computer at a high speed should be adopted (Li et al., 2018; Wen et al., 2019; Chan and Li, 2020).

On the basis of computer numerical simulation, the model not only can simulate the real wind shear of wind field, buy can also provide other useful physical quantities (such as temperature, moisture content and radar reflection factor, etc.). In addition, this model also reveals the process of the formation, the reason and development of wind shear. Using the three kinds of model above, we can establish the variable wind field around the airport environment.

The wind field data file should include the reflectivity and the airflow speed of *x*-*y*-*z*-directions. These data of wind field models are available in the following condition: the Frehlich/NCAR 3-component, 3-D Von Karman turbulence model, the AeroTech/NCAR interpolated model with superimposed Von Karman turbulence, the NASA TASS model and the NCAR cloud physics model (Yamazaki et al., 2022; Hon and Chan, 2022).

Common classification of wind shear and its characteristics:

1 *Working principle of infrared wind shear radar*: The velocity of downdraft flow has an approximate linear relationship with temperature. The colder the downdraft, the greater the wind speed. So, by detecting the temperature field, you can detect wind shear. Based on this principle, TPS developed and developed the infrared system, and successfully tested it. It is recorded that the wind shear can be detected 46 s in advance.

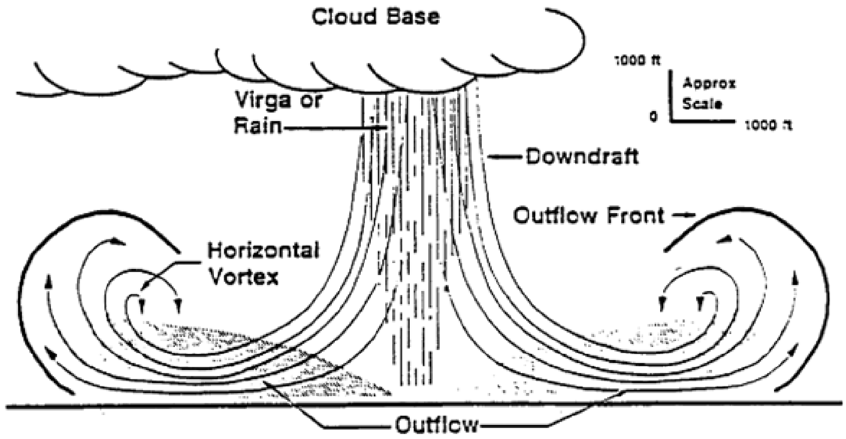
2 *Principle and application of microwave Doppler radar*: The characteristics of microwave Doppler radar: it has been successfully used in detecting wind shear on the ground for many years. It is less affected by the atmosphere and can be integrated with airborne weather radar. The warning time is 30 to 40 s.

3 *Principle and application of laser Doppler wind shear radar*: Wind shear measurement by LiDAR is characterised by high accuracy and small size. A laser system is used as an example. The warning time is 20 to 40 s, which can detect the radial wind speed.

2 Experiments

In our preliminary study, because it is unable to get the data from airport radar system and the tower, we select the aforementioned Three Wind Shear of Wind field in the model the second study. According to NASA's technical report 'A Method for 3-D Modelling of Wind Shear Environments for Flight Simulator Applications', it designs the simple wind engineering field model, which leads to the aircraft in flight in danger. It is also a typical low-level wind shear of micro-flow model. In the model, the time change of wind speed is not under considering, because wind speed change usually far less than the speed of the plane. So the wind speed changes with time can be neglected. The simulation of wind field profile is shown in Figure 1.

Figure 1 The profile of wind shear



Wind field parameters with the intermediate variable of the model:

The centre of the wind field in *X*-direction: *XC* 6000 ft

The centre of the wind field in *Y*-direction: *YC* 6000 ft

The characteristics radius of wind field: *R* 2000 ft

The limit of wind field height: *HT* 1000 ft

The initial reference velocity: VZO 25 ft/s

The distortion factor of wind filed in *XY*-direction: *GX*, *GY* 0

The wind field strength gain factor: GVZ 1.0

The unit conversion: 1 ft 0.3048 m

The height of plane: *H*

The coordinates of plane in *Y*-direction: *Y*

The coordinates of plane in *X*-direction: *X*

The velocity components of wind field in *X*-direction: *VXX*

The velocity components of wind field in *Y*-direction: *VYY*

The velocity components of wind field in *Z*-direction: *VZZ*

We made a simple micro-strike critical flow under the wind field model. It simulates the wind field within the scope of the whole space in X, Y and Z three directions of wind speed. The specific simulation process is as follows:

(1) *The vertical airflow speed*: The calculation of radial distance of the plane:

$$XR = X - XC \tag{1}$$

$$YR = Y - YC \tag{2}$$

$$RC = \sqrt{\left(X - XC\right)^2 + \left(Y - YC\right)^2} \tag{3}$$

The calculation of *RA*, on a plane position, critical flow distortion factor and position parameters:

$$CA = \frac{XR * GX + YR * GY}{RC} \tag{4}$$

$$RT = R * CA \tag{5}$$

$$RA = RT + \sqrt{RT^2 + R^2 * \left(1 - GR^2\right)} \tag{6}$$

Calculation of the speed in airflow direction *Z*:

If $H >= HT$; VZH=GVZ*VZO (7)

Or $$VZH = GVZ * VZO * \left(1 - \left(\frac{HT - H}{HT}\right)^2\right) \tag{8}$$

The radial ratio : $$RR = \frac{RC}{0.7 * RA} \tag{9}$$

If $RR < 1.0$; $VZZ\left(K, I, J\right) = -VZH * ft$ (10)

If $RR > 2.0$; VZZ=0 (11)

If $1.0 =< RR =< 2.0$;

$$VZZ\left(K, I, J\right) = \text{-}VZH * ft * \left(1 - \cos\left(RR * pi\right)\right)/2 \tag{12}$$

By the speed of the *Z*-axis, we see that the vertical gradient in only $1.0 =< RR =< 2.0$, other space area of *Z* to the velocity component is a constant value.

(2) *The speed of the horizontal airflow*: When RR=1.0

If $H >= HT$; $VRR = 0$ (13)

and $$VRR = 0.7 * GVZ * VZO * \frac{RA}{HT^2} * \left(HT - H\right) \tag{14}$$

If $H < 50$; $VRR = VRR * \left(0.75 + 0.005 * H\right)$ (15)

If $RR < 1.0$; $VR = RR * VRR$ (16)

If $1.0 =< RR =< 2.0$;

$$VR = VRR * \left(RR - 1.3 * \left(RR - 1\right)^3 + 0.45 * \left(RR - 1\right)^6\right) \tag{17}$$

If $RR > 2.0$; $VR = \frac{2.3 * VRR}{RR}$ (18)

The calculation of the speed in airflow direction *XY*:

$$VXX = \frac{XR * VR * ft}{RC} \tag{19}$$

$$VYY = \frac{YR * VR * ft}{RC} \tag{20}$$

The leakage/false alarm rate is the main factor that determines the reliability of the whole airborne low altitude wind shear detection system. The accuracy of wind speed measurement and detection distance determine whether the accurate advance warning can be achieved. Ground clutter is one of the main factors that cause the leakage/false alarm of microwave radar system, and clutter suppression is a very difficult problem. This problem has not been well solved until now because the type, characteristic and distribution of clutter source are not well understood and the technical means are limited. However, the airborne microwave Doppler radar low-altitude wind shear detection system must consider the miss/false alarm rate, the specific performance index is still difficult to determine, which needs to be obtained through a lot of actual flight tests and statistics. The probability analysis of Monte Carlo method is used in the statistics, and a lot of numerical simulation is also required. However, with the ground system data as a reference, the miss/false alarm rate indicators should be at least below 10^{-4}.

3 Results and analysing

At the beginning of the simulation, the initial position of the aircraft and the pointing of the antenna are given. Along with the simulation process, after the completion of an azimuth scan, the position update of the aircraft is adjusted according to the speed of the aircraft and the time required for a scan. The scanning azimuth and pitch angle of the antenna are adjusted according to the scanning mode of the antenna, and the scanning line is adjusted, and then the scanning is carried out from the opposite direction of the azimuth Angle. The simulation scan process is repeated in this way. After each azimuth scan, the rain echo and ground clutter data generated are processed in real time and then the risk factors are calculated, characteristic parameters are extracted and alarms are output.

We have 12 KFT × 12 KFT × 1 KFT airport space area for a 120 × 120 × 50 mesh, each grid size of 100 ft × 100 ft × 20 ft. In features of radius R = 2000 ft, we take an extension of the wind shear within 1 to 3 km in diameter. X is perpendicular to the plane heading in the right is positive, and y for the plane heading for is positive, z is the height above the runway positive upward. The centre of the wind field is in (X, y) = (6 KFT, KFT). We establish a three-dimensional wind field. The following three pictures are under the condition z = 300 ft, and the size of the velocity components in all directions. Figure 2 shows the component speed in z-direction, Figure 3 presents the velocity component in x-, y-directions, and Figure 4 shows the speed of the horizontal direction. From Figure 2, we can see the vertical height direction of the velocity change.

The following three figures are respectively in vertical height changes, x = 5800 ft, the wind speed along the y-direction change, Figure 5 for x to speed, Figure 6 for y to speed, Figure 7 for z to speed, the blue line shows the z = 200 ft, the green line shows the z = 500 ft, the red line shows the z = 800 ft. We can see that when x to determine, with the increase of height of z, x and y to gradually become smaller, the speed of the z to gradually increase the speed of, in accordance with our micro under the wind speed characteristic of critical flow. As we can see from Figure 6, the characteristic of wind field radius is 2000 ft.

Figure 8 shows when x = 5500 ft, y = 5500 ft x, y, speed changes in z-direction with height of z. The blue curve stands for the speed of z and red curve presents x, y speed changes. Figure 9 shows when x = 5000 ft, y = 5500 ft, the speed changes of x, y, z with height of z, the blue curve refers to the speed changes of z, the red curve refer to speed changes of y and the green curve to speed changes of x. This figure reflects the vertical gradient change of wind speed.

Figure 2 The component speed in z-direction (z = 300 ft) (see online version for colours)

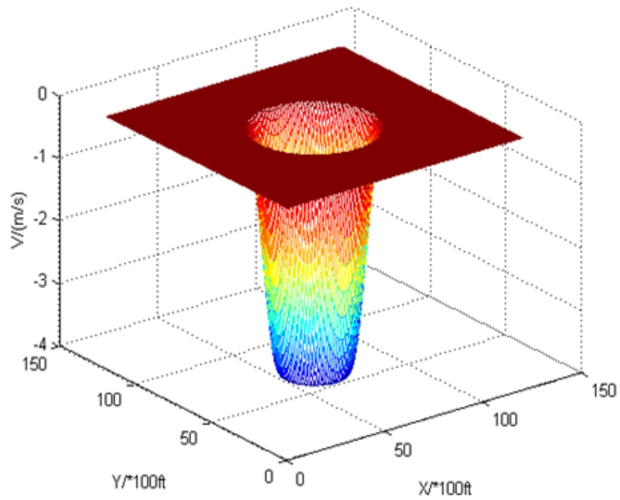


Figure 3 The component speed in xy-direction (z = 300 ft) (see online version for colours)

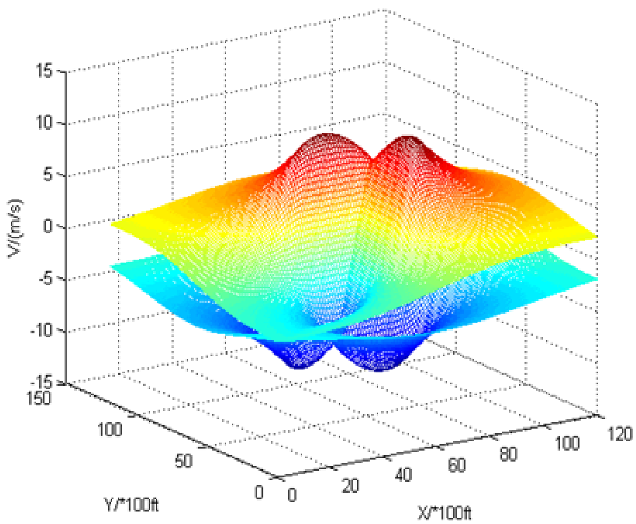


Figure 4 The component speed in horizontal direction (z = 300 ft) (see online version for colours)

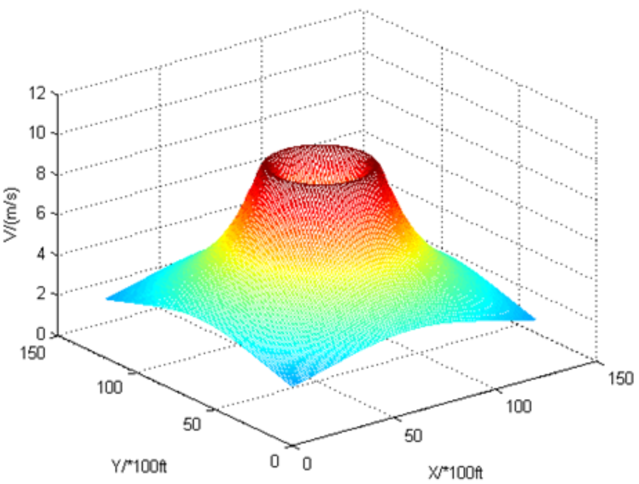


Figure 5 The speed in x-direction (z = 5800 ft) (see online version for colours)

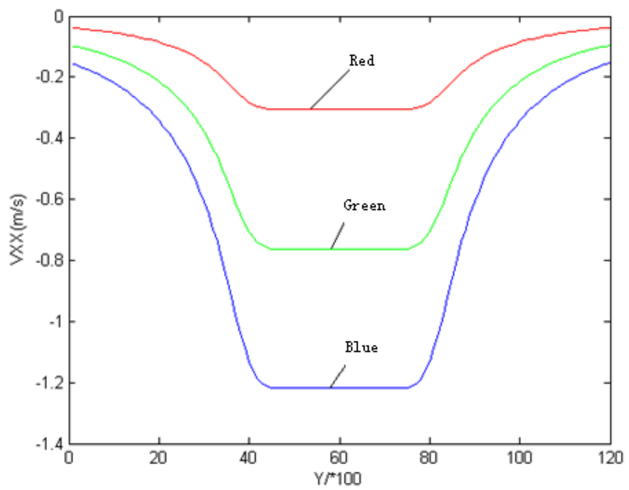


Figure 6 The speed in y-direction (z = 5800 ft) (see online version for colours)

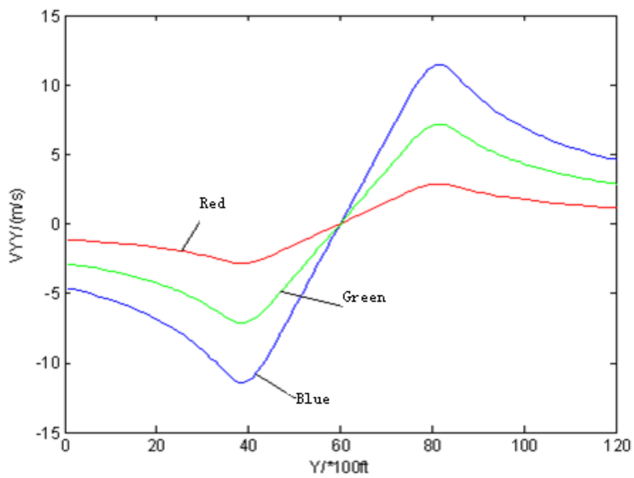


Figure 7 The speed in z-direction (z = 5800 ft) (see online version for colours)

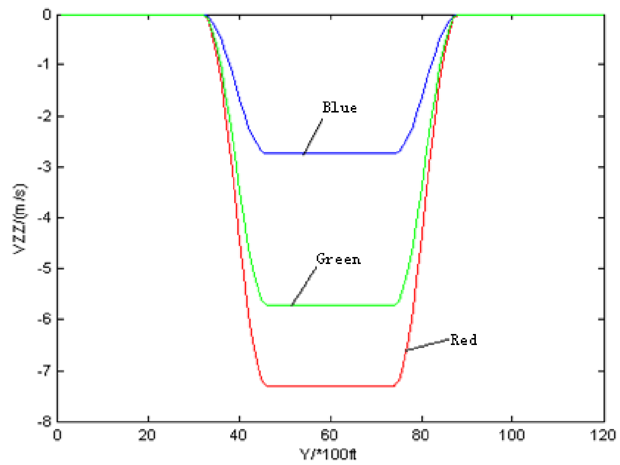


Figure 8 speed changes with height of z (x=5500 ft, y=5500 ft) (see online version for colours)

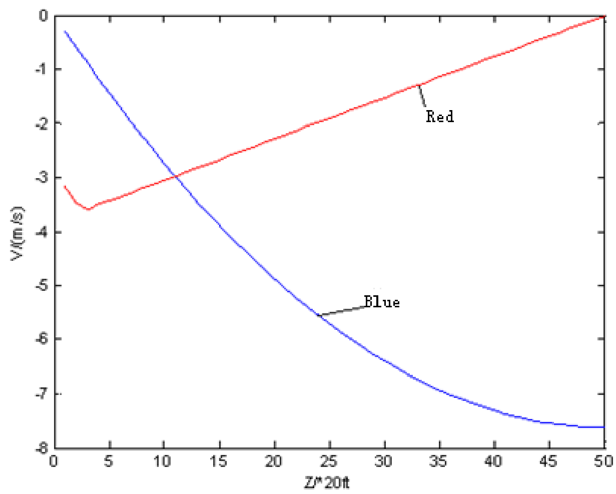
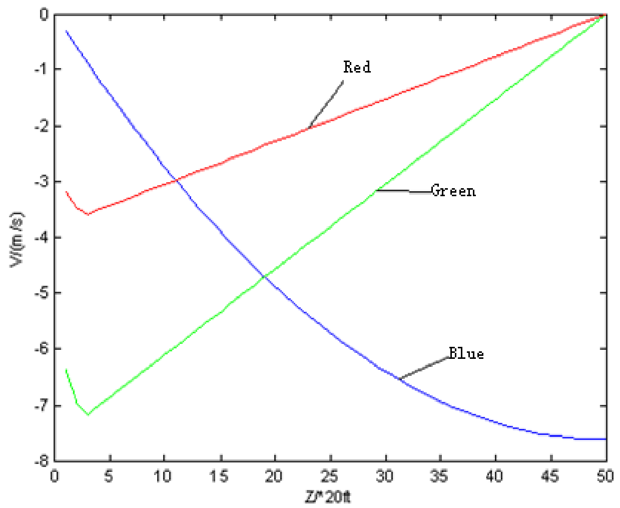


Figure 9 Speed changes with height of z (x = 5000 ft, y= 5500 ft) (see online version for colours)



In the development of wind shear detection technology, many signal processing algorithms have been proposed, such as Pulse Pair Processing (PPP) method, Fast Fourier Transform (FFT) method, Kalman Fi1ter filtering method, Bayes estimation method, mode analysis method and so on. Each treatment method has different advantages and disadvantages. In airborne radar, due to the constraints of many factors such as volume, weight, real-time performance and even product price, the applicable signal processing method should be the one with small computation amount, fast computation speed, alarm probability, false alarm probability and alarm leakage probability that meet the requirements. At Present, Pulse Pair (PPP) method and frequency domain estimation (FFT) method are the most used wind shear signal processing methods for airborne radar in engineering.

4 Conclusion

Three wind shear wind field modelling methods have been introduced in this paper: the first is the airport of weather radar network and all kinds of monitoring network based on the measured data calculation, the second is the wind shear wind field model with a common engineering of simple model, and the third is used to describe small scale meteorological atmospheric dynamics equation and physical equation. Then a simple model of engineering is shown in this paper. It briefly describes the modelling, the basic principle of the wind field physical model and it carries on the simulation. The simulation results are given, which are analysed and prove our conclusion.

Acknowledgements

Project Supported by Science and Technology Innovation Talent Project of Henan Province (21HASTIT021), Major Science and Technology Projects of Xinxiang City (21ZD009).

References

Baa, E.G. and Lai, YC. (1993) 'New signal processing developments in the detection of low-altitude windshear with airborne Doppler radar', *Record of the IEEE National Radar Conference*, pp.269–274.

Baxa, E.G. (1993) 'New signal processing developments in the detection of low-altitude wind shear with airborne Doppler radar', *Proceeding of IEEE National Radar Conference*, IEEE.

Britt, C.L. and Kelly, C.W. (1990) *User Guide for an Airborne Wind Shear Doppler Radar Simulation (AWDRS)*, NASA Langley Research Center, Hampton.

Chan, P.W. and Li, Q.S. (2020) 'Some observations of low level wind shear at the Hong Kong International Airport in association with tropical cyclones', *Meteorological Applications*, Vol. 27, No. 2. Doi: 10.1002/met.1898.

Hon, K.K. and Chan, P.W. (2022) 'Historical analysis (2001–2019) of low-level wind shear at the Hong Kong International Airport', *Meteorological Applications*, Vol. 29, No. 2. Doi: 10.1002/met.2063.

Kunkel, M.W. (1992) *Spectrum Modal Analysis for the Detection of Low-Altitude Windshear with Airborne Doppler Radar*, NASA Contractor Report 4457 DOT/FAA/RD-92/21, NASA, USA.

Li, D.A.R., Zhao, W.K., Zhao, S.J. and Sun, X.J. (2021) 'Numerical simulation for wind shear detection with a glide path scanning algorithm based on wind', *IEEE Sensors Journal*, Vol. 21, No. 18, pp.20248–20257.

Li, H., Zhou, M., Guo, Q., Wu, R. and Xi, J. (2016) 'Compressive sensing-based wind speed estimation for low-altitude wind-shear with airborne phased array radar', *Multidimensional Systems and Signal Processing*, Vol. 7, pp.1–14.

Li, J.L., Wang, X.F. and Yu, X. (2018) 'Use of spatio-temporal calibrated wind shear model to improve accuracy of wind resource assessment', *Applied Energy*, Vol. 213, pp.469–485.

Wen, B.R., Tian, X.L. and Wei, K.X. (2019) 'Wind shear effect induced by the platform pitch motion of a spar-type floating wind turbine', *Renewable*, Vol. 135, pp.1186–1199.

Widrow, B. (2005) 'Thinking about thinking: the discovery of the LMS algorithm', *Signal Processing Magazine IEEE*, Vol. 22, pp.100–106.

Widrow, B. and Walach, E. (1984) 'On the statistical efficiency of the LMS algorithm with nonstationary inputs', *IEEE Transactions on Information Theory*, Vol. 30, pp.211–221.

Widrow, B., Clover, J.R. and Mccool, J.M. (1975) 'Adaptive noise cancelling: principles and application', *Proceedings of the IEEE*, Vol. 63, pp.1692–1716.

Widrow, B., Mccool, J. and Ball, M. (1975) 'The complex LMS algorithm', *Proceedings of the IEEE*, Vol. 63, pp.719–720.

Widrow, B., Mccool, J.M. and Larimore, M.G. (1976) 'Stationary and nonstationary learning characteristics of the LMS adaptive filter', *Proceedings of the IEEE*, Vol. 64, pp.1151–1162.

Yamazaki, Y., Arras, C. and Stolle, C. (2022) 'Examining the Wind Shear Theory of Sporadic E With ICON/MIGHTI Winds and COSMIC-2 Radio 2 Occultation Data', *Geophysical Research Letters*, Vol. 49, No. 1. Doi: 10.1029/2021GL096202.