Study on the influence of attitude angle on lidar wind measurement results

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Abstract: When carrying on wind profile measurement of offshore wind farm by shipborne Doppler lidar technique, the ship platform often produces motion response under the action of ocean environment load. In order to measure the performance of shipborne lidar, this paper takes two lidar wind measurement results as the research object, simulating the attitude of the ship in the ocean through the three degree of freedom platform, carrying on the synchronous observation test of the wind profile, giving an example of comparing the wind measurement data of two lidars, and carrying out the linear regression statistical analysis for all the experimental correlation data. The results show that the attitude angle will affect the precision of the lidar. The influence of attitude angle on the accuracy of lidar is uncertain. It is of great significance to the application of shipborne Doppler lidar wind measurement technology in the application of wind resources assessment in offshore wind power projects.

1. Introduction

With the rapid development of global offshore wind power, our government has also increased the development and utilization of offshore wind energy resources. Offshore wind power industry has a bright future, and it\textsuperscript{[1]} will gradually develop into large-scale and deep sea areas in the future. The abundance of wind energy resources and changes will directly affect the development cost and investment benefit. Therefore, at the beginning of the development of offshore wind energy, it is essential to collect the short-term and long-term wind profile data of high precision and high reliability over relevant sea areas and in the corresponding height range, which is an important basis for offshore wind energy assessment, wind field location and offshore wind field operation and maintenance. In accordance with the standards of IEC, the common method of collecting offshore wind profile data is to build a corresponding number of offshore wind towers in the corresponding sea areas. However, the wind towers are only suitable for long-term wind profile data collection, which is obviously inappropriate for short-term measurements, whether from design and construction, costs and difficulty of operation and maintenance, or flexibility of using.

Shipborne lidar systems gain more and more in importance for the realisation of cost-efficient offshore wind resource assessments. These kinds of systems may not only offer measurement data that are more complete than those from present offshore meteorological masts (further measurement heights due to the used lidar technology) but have also significant advantages in terms of the associated costs for the provision, installation and final removal of the devices. Before applying a shipborne lidar system within an offshore wind resource assessments campaign, its performance needs to be tested and verified according to a well-defined scheme. G.A Cool\textsuperscript{[2]} used the numerical model programs of lidar to study the influence of ocean parameters on wind measurement results of floating lidar. G. Wolken-Mohllmann\textsuperscript{[3]}
used the shipborne lidar wind measurement technology to observe the wake wind of the offshore wind field. Germany Fraunhofer IWES [4] commercialized shipborne lidar technology for offshore wind resource assessment. At home, Songhua Wu [5] was the first one to study the wind profile data of offshore wind fields through Dongfanghong No 2 equipped with doppler lidar, and accumulated a large number of observation data of horizontal wind speed and vertical wind speed of sea-air boundary layer. However, due to the lack of comparative test conditions, the influence of the change of ship attitude on the accuracy of doppler laser radar was not concluded.

In order to promote the application of shipborne lidar system into China's offshore wind power project, reducing the cost of offshore wind resource assessment to bring the greatest benefits to the owners. In this paper, the experiment is designed to study the influence of attitude angle (roll and pitch) on the accuracy of the lidar. A lot of experimental data are accumulated. Based on the experimental data, the wind speed and wind direction of two doppler lidar are analyzed by linear regression analysis. In this paper, the influence of attitude angle (roll and pitch) on the accuracy of laser radar is studied by design experiment. A lot of experimental data are accumulated. Based on the experimental data, the wind measurement data of two doppler lidar were analyzed by linear regression in wind speed and wind direction. It is of great significance to wind power curve evaluation and certification, exploration and micro-sitting and wake observation of wind field in offshore wind power projects with the technology of shipborne lidar wind measurement applied into.

2. Wind field inversion principle

Laser technology is one of the most mainstream laser measurement technologies in the world. With its own advantages and characteristics, laser measurement technology can not only simultaneously measure data of wind speed and wind direction at different heights, get the same wind shear analysis results of the wind tower, and the measurement data is more abundant (horizontal wind, vertical wind, inflow angle etc. at different heights). In March 2017, IEC 61400-12-1:2017, a new standard issued by the International Electrotechnical Commission, used lidar as a wind field information measuring device to measure wind power curves and assess wind resources for wind fields. This paper selects the Molas B300 series which is independently developed by Nanjing Mulei Laser company.

The working principles of doppler lidar wind measurement: light incident on atmospheric molecules or aerosols, the backscattered signal relative to the incident laser signal will produce doppler frequency shift. Doppler frequency shift amount is proportional to the speed of target particle movement. By comparing the frequency difference between the backscattered signal and the outgoing light, the speed of the target particle can be obtained, and further, the wind speed also can be obtained. In the wind profile measurement, it is assumed that the wind field and atmospheric state (aerosol content, backscattering coefficient, etc.) at the same height are uniform. Using VAD-Velocity Azimuth Display. The technology is a method of fitting the wind profile information to a wind speed information obtained by continuously changing the azimuthal scanning at a fixed pitch angle.

Fig 1. three-dimensional scan of VAD

Consider a Cartesian coordinate system with x positive toward the east, consider a ground-based doppler lidar located directly below the origin of the coordinate system; its beam is directed at elevation angle $\alpha$ and is rotating about a vertical axis with the range gate set at slant range $R$ (horizontal range
r) so as to scan a horizontal circle centered at the origin. Assume that the lidar receives a return around the entire scanned circle from precipitation of fall speed $V_r$, traveling with the wind at horizontal speed $V_h$ and direction $\theta$ to the x axis (Fig 1). The azimuth variation of the mean radial velocity sensed by the radar is then given by

$$V_R(\beta) = V_h(\beta) \cos(\beta - \theta) \cos \alpha + V_f(\beta) \sin \alpha$$

$$= V_h(\beta) \cos \beta \cos \alpha + V_f(\beta) \sin \beta \cos \alpha + V_f(\beta) \sin \alpha$$

(1)

Where $V_R$ conventionally is positive toward the lidar and $V_f$ is positive downwards. The lidar display of $V_R$ as a function of $\beta$ is the VAD. $V_h$, $V_f$ is the velocity components. According to the obtained radial wind speed, the cosine function is fitted by the LM least squares method, and the three-dimensional wind field is finally inverted.

3. contrast test

3.1 Test survey

In CSSC Luzhou Zhenjiang Marine Auxiliary Machinery (E 119°33′63″; N 32°10′85″), simultaneously observing the wind speed and wind direction of twelve height layers at the same location through the opening of No 5 and No 6 Doppler lidar. The No 5 Doppler lidar is mounted on a fixed platform, and the No 6 Doppler lidar is mounted on a three degree of freedom platform, and the motion attitude of the three degree of freedom platform is controlled by setting different motion parameters. The comparative observation test lasted for one week (June 7, 2017-June 14, 2017). During the process of the experiment, static and dynamic attitude angles were observed. The lidar outputs data such as horizontal wind speed and vertical wind speed, wind direction, signal to noise ratio, data availability and so on for 1 second or 10 minutes. Due to the limitations of the test conditions, we take the average data of one minute for the large attitude angle (4° or more); and we take average data of ten minutes for small attitude angle (4° or below). This process requires the preparation of the corresponding program through matlab software to solve the 1 minute wind profile data. Finally, two laser radar synchronous observation data were analyzed by using linear regression through matlab software.

3.2 Test apparatus

As shown in Fig 2, apparatus for testing mainly includes three degree of freedom platform, wind measurement lidar, and SMC IMU attitude instrument. Three degree of freedom platform system, composed of Stewart mechanism, computer control system, drive system, pump station and other components, is a complex mechanical and electrical integration product. The down-platform is mounted on a fixed ground and the up-platform is a support platform. The computer control system realizes the movement of the three degrees of freedom of the movement platform by coordinating the stroke of the electro-hydraulic cylinder, that is, a heave motion in the Cartesian coordinate system and rotation.
around the two axes. The platform can be used for marine environmental test and multiple motion simulation, custom sea conditions, and custom motion performance. The leakage of oil and the automatic alarm of the system may occur during the use of the movement platform because of the high oil temperature of the hydraulic. Therefore, using the cooling water system as much as possible and the motion platform intermittently in the process of using, which causes the discontinuity of the wind profile data.

SMC IMU attitude instrument is mainly used to measure the instantaneous attitude of Doppler lidar. The basic working principle of the SMC IMU attitude instrument is based on the Newtonian mechanics law. By measuring the acceleration of the carrier in the inertial reference system, integrating it with time and transforming it into the navigation coordinate system so as to obtain the speed, yaw angle and location information in the navigation coordinate system. The system itself does not copy the output text data, so using the RS232 serial line in the process of test, debugging software through the serial port to output digital text data and save. Avoiding being close to the hydraulic pump as far as possible during the process of installation, making the installation location be as close as possible to the gravity position of lidar, and eliminating alignment deviation between lidar and gravity center location of attitude meter through setting the SMC inertial navigation software.

Doppler lidar uses the Molas B300 series developed by Nanjing Mulei Laser company, which has the characteristics of high spatial and temporal resolution, high wind measurement accuracy, low power consumption, stability and convenience. The core modules of lidar, such as fiber laser radar transmitter, laser transceiver system, high-speed data acquisition system and high-precision data processing software, are developed independently and achieving localization. The laser radar uses VAD technology to obtain the wind profile, and the measurement of the radial wind speed is carried out simultaneously at 12 height layers with the elevation of 62 ° in 8 directions of east, west, south, north, southeast, northeast, southwest and northwest, and finally the LM least squares method is used to invert the 3D wind field. Three dimensional freedom platform, attitude indicator, part of the performance parameters of laser radar as shown in Tab 1.

| Tab 1. Experimental instrument performance parameters |
|------------------------------------------------------|
| **Molas B300 lidar** | **3-DOF motion platform** | **SMC IMU attitude indicator** |
| Sampling frequency | 1s | Dead weight 3000 kg | Static angle accuracy 0.02 °R |
| Roll range | 40-300 m | ±15 ° | Dynamic angular accuracy 0.02 °R |
| Height level | 12 | Pitch range ±10 ° | Roll accuracy 0.03 °R |
| Speed accuracy | 0.1 m/s | Heave range ±1 m | Sampling frequency 0.01 s |
| Direction accuracy | 1 ° | Power 341 KW | Roll range ±30° |
| Speed range | 0-60 m/s | Supply voltage AC380 V | Heave range ±10 m |
| Temperature range | -30-50° | Actuator stroke 2.1 m | Heave accuracy 5 cm |
| Humidity range | 0-100 | Cooling method | Acceleration accuracy 0.01 m²/s |

4. Selection of test conditions

Fig 3 and Fig 4 show the wind profile data observed by two Doppler lidar at 7 o'clock on June 8, 2017, in which a Doppler lidar is at the condition of rolling 3.4 ° and pitching -3.1 °. Seeing from figure 2 and figure 3, maximum wind speed, minimum wind speed and wind direction of ten minutes at the 12 height levels are obviously different, but the average wind speed in ten minutes, two sets of laser radar measurement results have good consistency. It can be concluded that attitude angle has little influence on the average wind speed of lidar wind measurement data, but the influence on wind direction,
maximum wind speed and minimum wind speed is relatively large.

Fig 3. Wind speed contrast chart

Fig 4. Wind direction rose chart

Fig 5 is a scatter diagram of the wind profile data of two lidar from 9:00 -11:00 of June 9, 2017. It can be seen from Fig 5a, b that the squared correlation of the wind measurement data of the two lidar (height 70 m) is achieved to more than 0.99 in the case of the roll angle (3.4 °) and the pitch angle (-3.1 °), and the slope of the curve is close to 1, which indicates a high degree of correlation of the two lidars wind measurement data. Fig 6 is the comparison diagram of the vertical wind speed of two lidars from 18:00 on June 8, 2017 to 20:00 on June 9, 2017. Figure 6 shows the obvious change of vertical wind speed of two lidars; Fig 7 is a random selection of the horizontal wind speed comparison diagram which shows that there is a small difference in the two horizontal wind speed, and the overall trend of the horizontal wind speed and vertical wind speed is the same. Therefore, the inclination angle has a great influence on the vertical wind speed and a small influence on the horizontal wind speed measured by the lidar.

Fig 5. Scatter plot of wind profile data(10min)

Fig 6. Vertical wind speed contrast chart

Fig 7. Horizontal wind speed contrast chart
In order to deeply study the influence of attitude angle on the results of wind measurement lidar, the attitude angles of five kinds of ships and two kinds of attitude angles which can be changed according to certain period are randomly simulated by three degree of freedom platform. The working conditions of test are shown in table 2. The linear regression analysis of the wind measurement data of the two lidars at 12 height levels is carried out by MATLAB software. The linear regression equation parameters are obtained by least squares method. Through this mathematical method, it is easy to find a statistical law to reflect the two data from a large number of observed scattered data, which can be expressed in the form of mathematical models.

| Case  | Roll | Pitch |
|-------|------|-------|
| Case 1 | 4.5  | -5.1  |
| Case 2 | 5.6  | -6.9  |
| Case 3 | 8.3  | -7.3  |
| Case 4 | 7.9  | -10.9 |
| Case 5 | 11   | -5.7  |
| Case 6 | ±3°  | 5s    |
| Case 7 | ±5°  | 5s    |

5. Comparison and analysis of test results

5.1 Effect of Static Attitude Angle on wind measurement lidar accuracy

In this paper, five kinds of attitude angles of the ship under the action of the marine environment load are simulated randomly by a three degree of freedom platform, and linear regression analysis of the measured profile is carried out. The average of 1 minute is selected as wind speed and wind direction. Fig 8 is a graph of the linear regression of wind speed and wind direction at 70 meters height measured by two doppler lidars under the five working conditions on June 8,2017.

![The scatter plot of Wind speed](image1.png)

![The scatter plot of Wind direction](image2.png)
Fig 8. scatter plot of the wind speed and wind direction

c The scatter plot of Wind speed

d The scatter plot of Wind direction

e The scatter plot of Wind speed

f The scatter plot of Wind direction

g The scatter plot of Wind speed

h The scatter plot of Wind direction

i The scatter plot of Wind speed

j The scatter plot of Wind direction
Fig 9 shows the squared statistical comparison diagram of linear correlation coefficient of the wind speed and wind direction at each height level under the conditions of five kinds of attitude angles. As can be seen from Fig 9 that the square wave of the correlation coefficient between the horizontal wind speed and the wind direction is very obvious under working condition 1. Under working condition 2 and 5, the square of the horizontal wind speed correlation coefficient is above 0.85 and the variation range is not large, but the square wave of the correlation coefficient of wind direction is obvious. The square of the correlation coefficient of the wind direction is small under working condition 3, and the square of the correlation coefficient of the horizontal wind speed decreases with the height increasing. Under working condition 4, the wind speed and wind direction show a good consistency, and the correlation coefficient of the square are 0.90; Under working condition 5, the square of the correlation coefficient of wind direction decreases slightly with height changing, while the square of the correlation coefficient of horizontal wind direction increases with height increasing. Summing up these five working conditions, from which can draw a conclusion: When the attitude angle is greater than 4 degrees, attitude angle affects the accuracy of lidar wind measurement, but there is no definite relation which can be used to express the influence of attitude angle on the lidar wind measurement accuracy. The influence of attitude angle on Doppler lidar wind measurement accuracy is uncertain.

5.2 Effect of dynamic Attitude Angle on lidar wind measurement accuracy
The influence of dynamic attitude angle on lidar wind measurement accuracy is simulated by using three degree of freedom platform. Due to the limitation of experimental conditions, simulation of two working conditions is carried out, and the follow-up will continue to improve. Fig 10 is a scattered plot of average wind speed and wind direction of 1 minute of two Doppler height lidar at 70 meters height level. As can be seen from figure a, the correlation coefficient is 0.9909, and the slope of the linear regression equation is 1.0446. As can be seen from Fig. c, the correlation coefficient was 0.9841, and the slope of linear regression equation is 0.9684; From Fig d, it can be seen that the correlation coefficient is 0.9729, the slope of the linear regression equation is 0.9625. It can be concluded from Fig. 10 that under the working condition 6, the offset of the two data is very small, the correlation coefficient is above 0.98, and the influence of movement response on the lidar wind measurement data is very small, therefore there is a strong correlation between the two lidar data. Under the working condition 7, the offset of the two data is also small, the correlation coefficient of the two is slightly lower, but also above 0.97. It is shown that the effect of movement response on the accuracy of the lidar wind measurement is small, and because of the limitation of the test condition, the conclusion that the angle range has the least effect on the lidar wind measurement data cannot be drawn.
Fig 10. Scatter plot of Wind profile data (1 min)

Fig 11 is a statistical contrast diagram of the square of the linear correlation coefficients of wind speed and wind direction at each height level under working condition 6 and working condition 7 in June 12, 2017. As can be seen from Fig 11, under working condition 6 and working condition 7, the correlation coefficient of wind speed is more than 0.96, which shows good consistency, while in working condition 7, there is a large error. From the analysis of the test results, we can draw a conclusion: under working condition 6 and working condition 7, the correlation coefficients of each height level are relatively high, and the movement response of the carrier has little influence on the average wind speed measured by lidar. However, the wind direction is affected by the movement of the carrier, and the influence of each height level is quite different.

Fig 11. The R-squared comparison of wind profile

6. Conclusion
In this paper, the linear regression analysis of two lidar wind measurement data is carried out by the
synchronous observation test. The following conclusions are drawn:

1) The 3° attitude angle has little effect on the average wind speed measured by the lidar, and there is a small difference between the measured maximum wind speed, the minimum wind speed and the wind direction.

2) There is a significant difference between the average wind speed and the wind direction measured at the attitude angle of more than 4°, but not the bigger the attitude angle, the greater the difference in the wind profile data. And the effect of the attitude angle on the lidar wind measurement data is uncertain.

3) The dynamic attitude angle has little effect on the measured wind speed measured by the lidar, and the obtained wind measurement data has a good consistency, but it has a great influence on the wind direction and has uncertainties.

It is worth noting that the conclusions obtained in this paper are based on the current limited experimental data, which will continue to be improved.

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