MOTIONAL BEHAVIOR ESTIMATION USING SIMPLE SPECTRAL ESTIMATION: APPLICATION TO THE OFF-SHORE WIND LIDAR.

*Salcedo-Bosch, A.*¹, *Rocadenbosch, F.*^{1,3} *Senior member, IEEE, Gutierrez-Antunano, M. A.*¹, *Tiana-Alsina, J.*²,

¹CommSensLab-UPC, Department of Signal Theory and Communications (TSC), Universitat Politècnica de Catalunya (UPC)

²Nonlinear Dynamics, Nonlinear Optics and Lasers (DONLL), Department of Physics (DFIS), Universitat Politècnica de Catalunya (UPC)

³Institut d'Estudis Espacials de Catalunya (Institute of Space Studies of Catalonia, IEEC), Barcelona, Spain, E-08034 Barcelona, Spain

ABSTRACT

This paper proposes two methods to estimate the so-called “characteristic motional period” of a floating wind-lidar buoy. These techniques aim to characterise the buoy’s pitch and roll tilting as simple harmonic motions by estimating their period. The “peak method” (PM) and the “3-dB method” are introduced as two different approaches to study the multi-modality of the wave motion. Additionally, the off-shore wind measurement campaign at Ijmuiden’s is briefly introduced to contextualize where data comes from and the added value of this study.

Index Terms— Wind, remote sensing, doppler lidar, wave motion, PSD

This work was supported via Spanish Government–European Regional Development Funds project PGC2018-094132-B-I00 and EU H2020 ACTRIS-2 (GA 654109). The European Institute of Innovation and Technology (EIT), KIC InnoEnergy project NEPTUNE (Offshore Metocean Data Measuring Equipment and Wind, Wave and Current Analysis and Forecasting Software, call FP7) supported measurements campaigns. CommSensLab is a María-de-Maeztu Unit of Excellence funded by the Agencia Estatal de Investigación (Spanish National Science Foundation).

1. INTRODUCTION

Offshore wind power generation has come up as a field of interest due to the homogeneous and strong winds available over the oceans [1]. Multiple offshore wind power farms have been installed and operated in Europe during the last decades [2]. Nevertheless, the related costs are still higher than in onshore wind farms and thus, cost optimization is a major concern regarding this technology. One of the main drawbacks to overcome is the resource assessment phase which requires precise measurements in the early stages of the project. Meteorological mast facilities have been employed traditionally for this purpose, nevertheless, its high cost of planning and environmental impact have arisen an interest in alternative atmosphere evaluation methods.

At this phase stage, there are diverse ways of gathering wind data, however, floating lidars have become in the recent years as one of the most suitable candidates to be accepted as an alternative to traditional methods [3]. When placed over a floating platform, Doppler lidars enable wind remote sensing without relying on expensive equipment. Moreover, since they are able to be re-deployed at multiple locations, they can assess the wind resource at large areas offering high versatility [4].

Floating lidar buoys suffer from both translational and rotational wave-motion influence [5]. One of the floating lidars main shortcomings is the Doppler effect of the sea-waves induced motion over the wind velocity vector retrieve as well as the atmospheric turbulence [5, 6]. Translational motion can easily be compensated, however, buoy's tilt induces an error on the wind measurements which is more difficult to be cancelled out. The measured wind velocity and atmospheric turbulence are affected by the Doppler shift induced by the sea-waves motion. Thus, in order to investigate the effect of the buoy tilt over lidar measurements, first, it is required to estimate wave-motion behaviour.

The buoy experiences an induced angular motion around the three coordinate axes, i.e., roll, pitch and yaw around x, y and z axes respectively. Yaw motion is characterised by low variations with time while roll and pitch show oscillatory motion behavior can be characterised to a first approximation as simple harmonic motion, i.e., by a characteristic harmonic amplitude and a period. Wave period and spectrum estimation are parameters of interest in oceanography which have arisen multiple

Fig. 1. Validation campaign location and picture of the experimental setup at Ijmuiden test site (North Sea)

techniques and studies for its characterisation [7] [8].

This paper proposes two methods to estimate the so-called "characteristic period" of the oscillatory motion by means of Spectral Estimation techniques. The methods presented next are based on Blackman-Tukey Power Spectral Density (PSD) estimation. Additionally, the results will be validated and discussed against experimental data gathered at the Ijmuiden test campaign (North Sea).

This paper is structured as follows: Sect. 2 presents the instrumentation of the Ijmuiden test campaign. Sect. 3 exposes the characteristic period estimation methods. Sect. 4 discusses the validity of the PSD estimation techniques and sect. 5 gives conclusion remarks and future investigation proposals.

Fig. 2. Example of Pitch and Roll temporal series

2. MEASUREMENT SETUP

The wind measurements were retrieved from the EOLOS floating lidar validation campaign [9] at IJmuiden test site, at approximately 75km West of the Netherlands. Fig. 1 shows the location of the IJmuiden facilities and the experimental setup provided with a 92-m tall met mast, and the EOLOS buoy with the floating lidar. The met mast is equipped with different sensors to gather main relevant environmental magnitudes. This measurement set-up allows to monitor the horizontal wind speed (HWS) at four heights (27, 58, 85 and 92 m above the Lowest Astronomical Tide (LAT)). Additionally a Triaxys wave buoy is also moored in the area to provide sea currents at different levels and wave measurements in the site. The reference wave period has been measured by the current profiler at a sampling period of 1 hour. The roll and pitch tilts samples have been gathered by the inertial measurement units (IMUs) at a sampling frequency of 10Hz as well. In Fig. 2 we can see an example of a pitch and roll temporal series measured by the IMUs during the test campaign.

3. METHODS

In this study we present two methods based on PSD estimation of the angular motion in order to determine the wave characteristic period. For simplicity, at this point we assume the one-dimension motional case in which both pitch and roll motions are strongly correlated.

3.1. PSD estimation

Among the different spectral estimation methods in the state of the art, Blackman-Tukey PSD estimation has been proposed due to its computation simplicity and estimation parameters [10]. The Blackman-Tukey method is essentially periodogram $P_{xx}(f)$ smoothing by means of its convolution with a smoothing window $W(f)$ [10]. It can be formulated as

$$P_{xx}^{BT}(f) = \int_{-1/2}^{1/2} P(\alpha)W(f - \alpha)d\alpha \quad (1)$$

Fig.3 shows the periodogram (grey) and smoothed periodogram (black) PSD spectral estimations of 10-min angular data time segments.

3.2. Characteristic period

The most straightforward method in order to compute the characteristic period from the estimated PSD is from the frequency corresponding to the PSD absolute peak. The Peak Method (PM) can be formulated as

$$T_{peak} = 1/f_{max} \quad \text{where} \quad f_{max} = \underset{f}{\operatorname{argmax}} PSD(f) \quad (2)$$

However, the PM may not be suitable for multi-modal cases in which the peak frequency is not completely representative of the PSD as there is more than one relevant spectral component (see Fig. 3b). Thus, an alternative method, the "3-dB method", is presented so as to take into consideration all the relevant spectral components, i.e., the frequency components within half height the peak value. The -3-dB region is determined by the frequency values at which the PSD is above the half of its peak value. The "3-dB method" defines the characteristic period from the arithmetic mean of the highest and the lowest frequencies within the -3-dB region.

$$T_{3-dB} = \left(\frac{f_{3-dB}^{min} + f_{3-dB}^{max}}{2} \right)^{-1} \quad (3)$$

Fig. 3. Examples of the PSD in monomodal and bimodal cases. (a) Monomodal case measured at 2015-05-15T01:00:00. (b) Bimodal case measured at 2015-05-15T00:50:00.

3.3. Reference wave period

The IMUs have a 10-Hz sampling rate [11] whereas the wave sensor sample period is of 1 hour. Typically, sampling period in wind industry is 10 minutes and thus, for future research, the estimated characteristic period has been computed over non-overlapping 10 minutes time segments so as to obtain a sampling period of 10 minutes. Nevertheless, in order to validate the estimation methods with the reference data, characteristic period has been resampled at 1 hour sampling period.

Fig. 4. Scatter plots of the estimated wave period against the wave sensor wave period. Red lines represent the linear regression of the scattered values and the black dashed lines are the ideal 1:1 correlation line. Wave periods have been obtained by applying the PM (a) and 3-dB (b) methods on the PSD of the motion signal.

4. RESULTS

The methods presented in sect. 3 have been applied to the tilt time series (Fig. 2) measured by the IMUs in the floating Doppler wind lidar during IJmuiden test campaign. In Fig. 4, the characteristic period time series obtained have been validated against the reference wave period time series. As discussed in [12], roll and pitch period correlation showed nearly correlated behavior, as evidenced by a correlation coefficient, $\rho = 0.54$. Therefore, study of the motional period considering only one dimension (either pitch or roll) has been considered meaningful enough for the method evaluation.

4.1. Discussion

Fig. 4 shows scatter plots comparing the reference wave period measured by the Tryaxis against the estimated wave period with the "PM" (Fig. 4a) and the "3-dB method" (Fig. 4b). In Fig. 4a we observe high misestimation with estimated values lying between 0 and 14 seconds whereas the reference values are within the 2 and 7 seconds limits. The linear regression of the data shows this behaviour with a slope of 1.5 and an independent term of -2.8. On the other hand, the "3-dB method" algorithm reveals less relevant underestimation at low wave periods and small overestimation at high wave periods as it can be observed in Fig. 4b. The linear regression for this graph has a slope of 0.87 and an independent term of 0.55 which approaches better the ideal 1:1 line.

The overall performance of the methods has been analyzed quantitatively through the correlation coefficient (ρ) and the root mean square error (RMSE). The correlation coefficients indicate better performance for the "3-dB method" with a $\rho = 0.62$ against a $\rho = 0.37$ obtained with the "PM". In addition, the RMSE for the "PM" is 1.97 and for the "3-dB method" 0.39, showing a remarkable reduction of the estimation error with the second procedure. Despite all the statistical indicators show better results for the "3-dB method", some misestimation can still be observed. This may be due to the fact that the algorithm considers equally relevant all the wave spectral components that lie within the -3-dB region.

5. CONCLUSIONS

Two characteristic-period methods have been presented to characterize roll and pitch motional behaviour of the off-shore wind lidar buoy under the simplifying assumption of harmonic motion. Both methods are based on Blackman-Tukey spectral estimation of the PSD of the angular time series. The PM computes the characteristic period from the PSD peak whereas the "3-dB method" determines it from the mean frequency of the -3-dB region. Both methods have been applied over tilt data gathered by IMUs on the lidar buoy during the IImuiden test campaign. The method has been evaluated by comparing the characteristic period computed by both algorithms against a reference wave period from a wave sensor. The "3-dB method" yielded better

results in terms of correlation (0.62 against 0.37 for the PM) and RMSE (0.39 against 1.97) but still showed misestimation at high and low periods. The accurate wave spectral characterisation is still a matter of interest regarding the "3-dB method". Moreover, roll-pitch crossed influence needs further insight to completely depict the wave motion behavior.

6. REFERENCES

- [1] Global Wind Energy Council, "Global wind energy outlook 2016," Global Wind Energy Council, Tech. Rep., Oct. 2016.
- [2] —, "Global wind energy report 2016: Annual market update," Global Wind Energy Council, Tech. Rep., Apr. 2017.
- [3] Carbon Trust, "Carbon trust offshore wind accelerator roadmap for the commercial acceptance of floating lidar technology," Carbon Trust, Tech. Rep., Nov. 2013.
- [4] Y. Pichugina, R. Banta, W. Brewer, S. Sandberg, and R. Hardesty, "Doppler lidar-based wind-profile measurement system for offshore wind-energy and other marine boundary layer applications," *J. Appl. Meteorol. Climatol.*, vol. 51, no. 2, pp. 327–349, 2012.
- [5] J. Tiana-Alsina, F. Rocadenbosch, and M. A. Gutierrez-Antunano, "Vertical azimuth display simulator for wind-doppler lidar error assessment," in *2017 IEEE Int. Geosci. Remote. Se. (IGARSS)*. IEEE, Jul. 2017.
- [6] O. Bischoff, I. Würth, P. Cheng, J. Tiana-Alsina, and M. Gutiérrez, "Motion effects on lidar wind measurement data of the EOLOS buoy," in *Proc. 1st Int. Conf. Renew. Ener. Off.*, RENEW 2014, Ed., Nov. 2014.
- [7] H. C. and K.-D. S., "Estimation of significant wave period from wave spectrum," *J. Ocean Eng. Technol.*, vol. 163, pp. 609 – 616, 2018.
- [8] E. Tannuri, J. Sparano, A. Simos, and J. D. Cruz, "Estimating directional wave spectrum based on stationary ship motion measurements," *Appl. Ocean Res.*, vol. 25, no. 5, pp. 243 – 261, 2003.

- 121 [9] M. A. Gutierrez-Antunano, J. Tiana-Alsina, F. Rocabosch, J. Sospedra, R. Aghabi, and D. Gonzalez-Marco, "A wind-
122 lidar buoy for offshore wind measurements: First commissioning test-phase results," in *2017 IEEE Int. Geosci. Remote
123 Se. (IGARSS)*. (IEEE), Jul. 2017.
- 124 [10] J. Proakis and D. Manolakis, *Digital Signal Processing (4th Edition)*, 4th ed. Prentice Hall, 2006.
- 125 [11] E. J. Werkhoven and J. P. Verhoef, "Offshore meteorological mast ijmuiden abstract of instrumentation report," Energy
126 Research Centre of the Netherlands (ECN), Tech. Rep., Feb. 2012.
- 127 [12] M. Gutiérrez, J. Tiana, A. Salcedo, and F. Rocabosch, "Estimation of the motion-induced horizontal-wind-speed stan-
128 dard deviation in an offshore doppler lidar," *Int. J. Remote Sens.*, vol. 10, no. 12, 2018.