Exprimental Study on the wave measurements of wave buoys

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Abstract

Wave measurement is of vital importance for assessing the wave power resources and for developing wave energy devices, especially for the wave energy production and the survivability of the wave energy device. Wave buoys are one of the most popular measuring technologies developed and used for long-term wave measurements. In order to figure out whether the wave characteristics can be recorded by using the wave buoys accurately, an experimental study was carried out on the performance of three wave buoy models, viz two Wavescan buoys and one ODAS buoy, in a wave tank using the European FP7 MARINET facilities. This paper presents the test results in both time and frequency domains and the comparison between the wave buoys and wave gauge measurements. The analysis results reveal that for both regular and irregular waves, the Wavescan buoys have better performances than the ODAS buoy in terms of accuracy and the Wavescan buoys measurements have a very good correlation with those from the wave gauges.

Keywords: wave measurement, wave buoy, ODAS buoy, Wavescan, wave resources.

1 Introduction

As the fossil energy is running out day after day, more projects are in process to exploit the power from the ocean taking advantage of various wave or tidal energy devices. Various wave, tidal and current energy converters have been developed to exploit the huge potential marine power, especially wave energy. According to Smith et al. (2011, 2013), 3 stages of resource assessment are needed to go when developing the wave energy: resource characterization, site assessment and resource and energy monitoring. During the process above-mentioned, the measurements of different characteristics in various sea states, including the wave, current, tide and wind parameters are very important and necessary for assessing the energy reserves and the productivity of the energy devices. Besides, researchers shall be able to evaluate the survivability and reliability of the energy devices more convincing if the extreme wave states can be measured accurately.

So far, several technologies for wave measurements have been developed and used for observations and measurements of waves around the world, such as the popular wave buoys (for instance, WaveRider, Wavescan and ocean data acquisition system (ODAS) buoy), ADCP (Acoustic Doppler Current Profiler), high frequency (HF) radar and even satellite imaging. All the measuring technologies differ fundamentally in their physical working principle. Wavescan buoy is a metocean data collection buoy measuring waves, current and meteorological parameters, and the buoy has a modular discus-shaped hull containing directional wave sensor, oxygen sensor, hydrocarbon sensor, etc. The ADCP sensor is usually mounted in a frame located on the seabed, and utilizes the Doppler shift for measuring the velocity of the water. HF radar system uses the horizon radar technology to monitor the surface of ocean based on remote sensing system, and the system is powerful for measuring waves over a large area.

Pandian et al (2010) has overviewed the recent technologies on wave and current measurement in detail. The overview showed that different instruments have their own advantages and disadvantages mainly related with the applications and needs. The high frequency radar is able to provide data for a wider area, and ADCP can provide real-time current information. However, for long-term (months or years) wave measurements, wave buoys are the most popular and cost effective technology due to its relatively easy installation/retrieval for different water depths, its measurement reliability and the continuous data transmission, and they are frequently referred as the standard method for wave measurement in the seas.

Conventionally, the wave buoys are moored in the single point mooring system, which allows enough flexibility to match the different wind, tide and wave conditions. However, the large flexibility may also induce a problem that whether the wave buoys are measuring the actual waves, especially for those very large short-crested waves, for which the wave buoys may move around and hence miss to record the largest waves. It is shown by Alleder et al. (1989) that during high sea states, the WaveRider tends to underestimate the spectral wave energy. It is also shown the wave buoys may response to the large waves when compare to conventional wave gauges (fixed-point measurement). Rademakers (1993) compared the time series of the sea surface elevation recorded by a fixed wave staff and a free floating buoy. It is showed the underestimation of wave energy by the buoys is induced by that the fixed wave gauge distorts the time series of the vertical motion of a water particle.

In order to figure out whether the wave characteristics can be recorded accurately using these wave buoys, an experimental study on the performance of 3 wave buoy models in a wave tank was carried out using the European FP7 MARINET facilities (free access to the European test facilities). According to Harald et al. (1999), the most central sea-state parameters are significant wave height, the mean period, the spectral peak period, etc., so we choose the 3 parameters mentioned as the criteria for these tests. Both time and frequency domain analysis and the comparison between the wave buoy and wave gauge measurements will be presented in this paper, and the accuracy of the wave buoy measurements will be examined using some statistical characteristics. Besides, mooring systems located at different water depths were adopted during the wave tank test, so that the effect of the mooring system for the wave buoys could be assessed.

2 Physical Model and Experiment Method

2.1 Physical model

During the wave tank test, the motions of wave buoys throw a variety of wave states are to be simulated. As the waves are dominated by gravity, the Froude similarity criteria are used to determine the scale for the buoy models, see Eq.(1). According to the definition of Froude number, the nexus among the velocity scale, the time scale and the length scale could be described as Eq.(2).

$$(\mathrm{Fr})_p = (\mathrm{Fr})_m \quad \textbf{(1)}$$

$$\lambda_v = \lambda_t = \sqrt{\lambda_l} \quad \textbf{(2)}$$

where Fr is Froude number, the subscript p represents the prototype, m represents the model; λ is the model scale, the subscript v represents velocity, t represents time and l represents length.

The prototypes for this wave buoy model test are Wavescan and ODAS buoys, the models' dimensions are calculated referred to the prototypes. The test models include 1:8 and 1:16 scaled Wavescan models and a 1:11.25 ODAS buoy model, see Figure 1. The Wavescan buoy models are in disc shape, 55 mm and 27.5 mm thick separately, and the radii are 163 mm and 81.5 mm respectively for the 1:8 and 1:16 models. The ODAS buoy model is in cylinder shape with a cone at the bottom and 115 mm thick, and the radius of the cylinder is 89 mm.

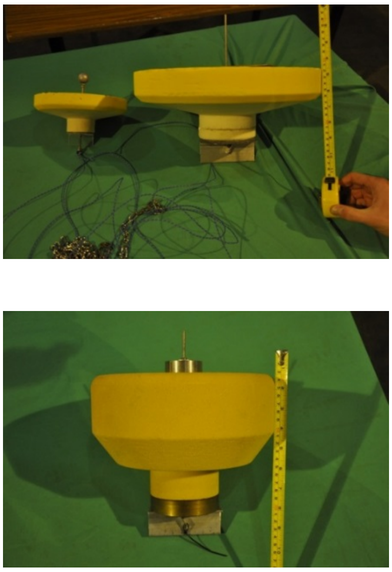

Figure 1 upper: Wavescan buoy models; lower: ODAS buoys model

Tests were conducted in the wave tank in Ecole Central de Nantes, France. The wave tank is 50 m long, 30 m wide and 5 m depth, with a constant surface water temperature 10-20℃. A segmented wave maker is located at one end of the tank composed of 48 paddles which are individually controlled by software, and could generate directional waves, including regular waves with maximum height of 1.1 m and irregular waves with maximum significant wave height of 0.6 m. At the other end of the wave tank, a parabolic rigid absorbing beach is located, at about 40 m away from the wave maker. The incident wave could be dissipated through the wave breaking processes during the wave tests. A 30 m wide moving bridge is equipped upon the wave tank to locate the instrumentations, including the wave gauges.

For the wave tank tests, the waves are determined by the wave height and period. With the length scale settled, the time scale could be easily calculated. Considering the capability of wave makers and the data readability, the prototypical wave states were chosen and scaled down as shown in Table 1 and Table 2. During the tests, there were 2 wave heights (H_m) and 4 wave periods (T_m) for the regular wave states, while for the irregular wave states, the Bretshneider spectrum were used with 6 different significant wave heights (H_S) and 6 peak periods (T_P) for long crest (LC for short) and short crest (SC for short) waves. The wave height and period could be assembled to obtain a variety of wave states for the tests, and the irregular wave states were numbered as shown in Table 2 for convenience.

Table 1 Regular wave states

H_m (m)	T_m (s)			
0.1	1.5	2.0	2.5	3.0
0.5	1.5	2.0	2.5	3.0

Table 2 Irregular wave states

H_S (m)	T_P (s)					
0.2	2 (01)		2.7 (02)		3.3 (03)	
0.3		2.3 (04)				
0.4			2.7 (05)		3.3 (06)	4 (07)
0.5				2.85 (08)		
0.6					3.3 (09)	4 (10)
0.75					3.3 (11)	

2.2 Experimental method

The incident waves are generated by the segmented wave makers during the wave tank tests, while the wave makers are controlled by software. In order to confirm the characteristics of the incident waves, three groups of wave gauges were installed in the wave tank for measuring the waves in the tank, so that the incident waves could be calibrated before the tests during both regular and irregular states. In addition, the measurements of the wave gauges would be referred as the benchmark for the wave buoy models in these tests.

After calibration, the buoy models would be located in the wave tank with a lack mooring system, with 2 or 3 reflective markers placed on every buoy model. The motions of the wave buoys in waves were measured using the Qualysis system, a non-intrusive measurement allowed to measure the motions of very small models (the model of 1:16 Wavescan weighs 220g). The time series of the motions of the buoy models could be recorded as the motions of the markers being captured with the frequency of 60 Hz by high resolution cameras located around the wave tank. The measurements of different buoy models during the same wave states will be compared mutually and with those recorded by the wave gauges. In addition, for the 1:16 Wavescan buoy model only, the mooring system was located at depth 5 m and 10 m in succession to investigate the influence on the measurements of buoy models from the mooring system.

3 Data Aquisation and Processing

As mentioned in section 2.2, the time series of the buoy models' motions were recorded by the Qualysis system during the wave tank tests. The Qualysis system capture the optical signals of the target objects and transform the signals into the Cartesian Coordinates we need. For these tests, the reflective light markers were placed on the buoy models, see Figure 2.

Figure 2 Markers on the model

3.1 Data processing

As the lack mooring system was adopted during the tests, the buoy models had 6 degrees of freedom to move, while the heave motion was the most concerned one. For every marker, the Cartesian Coordinates could be able to be described with a rotation and translation matrix, which shows the relative movements between the marker and the gravity center of the buoy model, see Eq. (3).

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} + \begin{pmatrix} \xi_x \\ \xi_y \\ \xi_z \end{pmatrix} \quad (3)$$

where $\begin{pmatrix} x \\ y \\ z \end{pmatrix}$ is the coordinates of any point in the buoy, $\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$ is the displacements between the point and the gravity center of the buoy, $\begin{pmatrix} \xi_x \\ \xi_y \\ \xi_z \end{pmatrix}$ is the translational displacements of the gravity center in the coordinate axis directions, and the rotation matrices $R = R_X R_Y R_Z$ or $R = R_Z R_Y R_X$ due to different rotation order, where R_X, R_Y, R_Z are functions about the pitch, roll and yaw motion, as shown in Eq.(4a-c).

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{pmatrix} \quad \textbf{(4a)}$$

$$R_y = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \quad \textbf{(4b)}$$

$$R_z = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \textbf{(4c)}$$

Where φ is the roll motion, θ is the pitch motion, ψ is the yaw motion.

With the coordinates of the markers, the movements of the gravity center of the buoy models can be deduced by computing the rotation matrix. Besides, the buoy models are axial symmetrical bodies so that the effects of the yaw could be ignored.

3.2 Time somain analysis

8 combinations of wave heights and periods were taken as the regular wave states during the wave tank tests. Time domain analysis are applied for the regular waves, and the cross-zero methods are used to calculate the wave characteristics, including the wave number, mean wave height, 1/3 wave height, 1/10 wave height, etc. For the typical regular waves, the mean wave height is equal to 1/3 wave height and 1/10 wave height so we take the mean wave height H_m and period T_m as our characteristic parameters. The time series of motions recorded by the wave gauges and buoy models are counted separately on the basis of zero-crossing criteria.

3.3 Frequency domain analysis

For the irregular waves, both long crest and short crest, the generated waves are dominated by the spectral characteristics: significant wave height H_S and the peak period T_P. For the purpose of obtaining the spectral characteristics recorded by the wave gauge and buoy models, the Fast Fourier Transform (FFT) algorithm is applied on the calculations for the wave buoy models' data during irregular waves.

The wave energy density spectra *S(f)* are transformed from the time series of the movements of the buoy models with the aid of FFT algorithm, where *f* represents frequency. The spectral moments (m_n) of the energy density spectral are defined as Eq.(5).

$$m_n = \int f^n S(f) df \quad \textbf{(5)}$$

where integer n is the order of the moments.

With the spectral moments, the wave characteristics can be derived using Eq.(6).

$$\begin{cases} H_S = 4\sqrt{m_0} \\ T_m = m_0/m_1 \\ T_P = 1.296 T_{\mathrm{m}} \end{cases} \quad \textbf{(6)}$$

where H_S is the significant wave height, T_m is the mean wave period and T_P is the spectral peak wave period, and the linear ratio is empirical coefficient for the Bretshneider spectrum.

4 Results and Discussion

For the wave characteristics calculated, the correlation coefficient (CC), the root mean square errors (RMSE) and the relative errors (RE) are introduced as statistical parameters to estimate the correlation and the closeness of the measurements by the wave buoy models with the wave gauges.

For the characteristics measured by the buoy and wave gauge, denoted as two group of data (X_b, X_w), the statistical parameters are given as

$$\mathrm{CC}(X_b, X_w) = \frac{\sum(x_b - \overline{x_b})(x_w - \overline{x_w})}{\sqrt{\sum(x_b - \overline{x_b})^2 \sum(x_w - \overline{x_w})^2}} \quad \textbf{(7)}$$

$$\mathrm{RMSE}(X_b, X_w) = \sqrt{\frac{1}{n}\sum (x_w - x_b)^2} \quad \textbf{(8)}$$

$$\mathrm{RE}(X_b, X_w) = \frac{\mathrm{RMSE}(X_b, X_w)}{\overline{x_b}} \times 100\% \quad \textbf{(9)}$$

where the subscripts *b*, *w* are short for 'buoy' and 'wave gauge' seperately and *n* represents the count of the data. In order to investigate the performance of different type of buoy models, the inter-comparisons are performed during regular and irregular wave states. The internal comparisons are also conducted between large and small scaled Wavescan buoys and between Wavescan buoy using different mooring systems.

4.1 Wave measurements by the buoy models

The wave characteristics calculated by the buoy models are compared with those by the wave gauges and 3 statistical parameters are obtained, see Table 3 and Table 4. The correlation coefficient is dimensionless and shows the closeness between two groups of data, while RMSE shares the same dimension with the data and indicates the errors between the data and percentage RE reveals the degree of error deviation.

Table 3 Statistic parameters for regular waves

	1:16 Wavescan		1:8 Wavescan		ODAS buoy	
	H_m (m)	T_m (s)	H_m (m)	T_m (s)	H_m (m)	T_m (s)
Correlation Coefficients	0.9953	0.8847	0.9563	0.8406	0.9958	0.7534

Root Mean Square Error	0.0830	0.0710	0.1599	0.1650	0.0738	0.0676
Relative Error	3.84%	17.35%	7.22%	40.30%	3.41%	16.52%

Table 4 Statistic parameters for irregular waves

	1:16 Wavescan		1:8 Wavescan		ODAS buoy	
	H_S (m)	T_P(s)	H_S(m)	T_P(s)	H_S (m)	T_P(s)
Correlation Coefficients	0.9984	0.9938	0.9963	0.9744	0.9894	0.9649
Root Mean Square Error	0.0225	0.0609	0.0296	0.1145	0.0360	0.1256
Relative Error	3.47%	1.87%	3.79%	3.05%	3.90%	2.27%

In General, for wave heights measurements, all the buoy models show very good correlation with the wave gauges with CCs exceeding 0.95 during both regular and irregular wave states. The RMSEs during irregular waves seem less than those during regular waves: take the 1:16 Wavescan buoy model as an example, the RMSE for mean wave height is 0.0802m during regular wave states while the RMSE for significant wave height is 0.0225m during irregular wave states. On the other side, for wave periods measurements, the buoy models show much better performances during irregular wave states. All the REs for wave peak period are beneath 5% while for the regular wave states, the REs are quite large respectively, with a minimum of 16.72%.

Accordingly, for wave measurements, all the buoy models show good agreements with the wave gauges, especially during irregular wave states. The statistical parameters also reveal that, for both regular and irregular waves, the 1:16 Wave scan buoy model shows best correlation with the wave gauges and has the smallest measurement errors. The performances of different buoy models are discussed in the inter-comparison sections as follows.

4.2 Internal comprarisons among the buoy models

In order to show the measurements performance clearly, the wave characteristics calculated from the data recorded by the buoy models and wave gauge are drawn into one figure so that the inter-comparison can be more distinct. For the regular wave states with the height 0.1m, the buoys didn't record the wave motions completely, which may be due to the markers sheltered from the cameras.

For the regular waves with the height 0.5m, the measurements by the 3 buoy models contrasted with those by the wave gauge are shown in Figure 3, where the axis R1-R4 are short for regular wave state numbers, the red column is the results by the 1:16 Wavescan buoy model, the green column the 1:8 Wavescan buoy, the blue column the ODAS buoy and the black line with square is results by the wave gauge . For the regular wave states, the ODAS buoy model and smaller Wavescan buoy model show better agreement with the wave gauge, while the larger one lost one group of data and the characteristics show large deviation from those recorded by the wave gauge.

On the whole, the smaller Wavescan buoy and ODAS buoy show very good performance on measuring the wave heights, while the 2 buoy models couldn't record the accurate wave periods both during the regular waves, which we can also see from Table 3. In addition, the bigger Wavescan buoy model doesn't perform well during the tests, especially for wave periods.

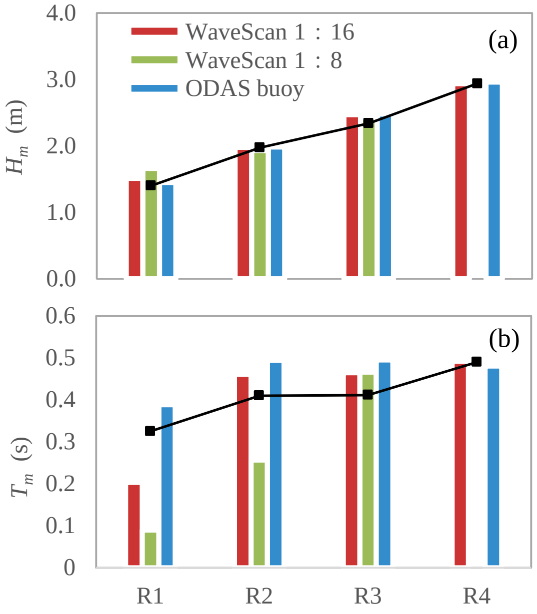

Figure 3 measurements for H_m (a) and T_m (b) during regular wave states (R1-R4)

For the irregular wave states, the measured wave characteristics by the wave buoy models are shown in Figure 4 and all the buoy models results are compared with those of the wave gauge. As there are many wave states, including some extreme cases, a lot of data have missed and we can see that from the figures. The results indicates that the 1:16 Wavescan buoy models has completely recorded all the wave states, while the other 2 buoys lost some data for cases LC/SC04, etc. The smaller Wavescan buoy model shows distinctively accurate and complete measurements for the H_S and T_P, and the measurements by the other models are good except the missed cases.

It's quite interesting that the measurements by the buoy models during irregular wave states are better than those during regular wave states. Besides, the buoy models tends to overestimate the mean wave periods during regular waves, while they tend to overestimate the significant wave heights during irregular waves but underestimate the peak period.

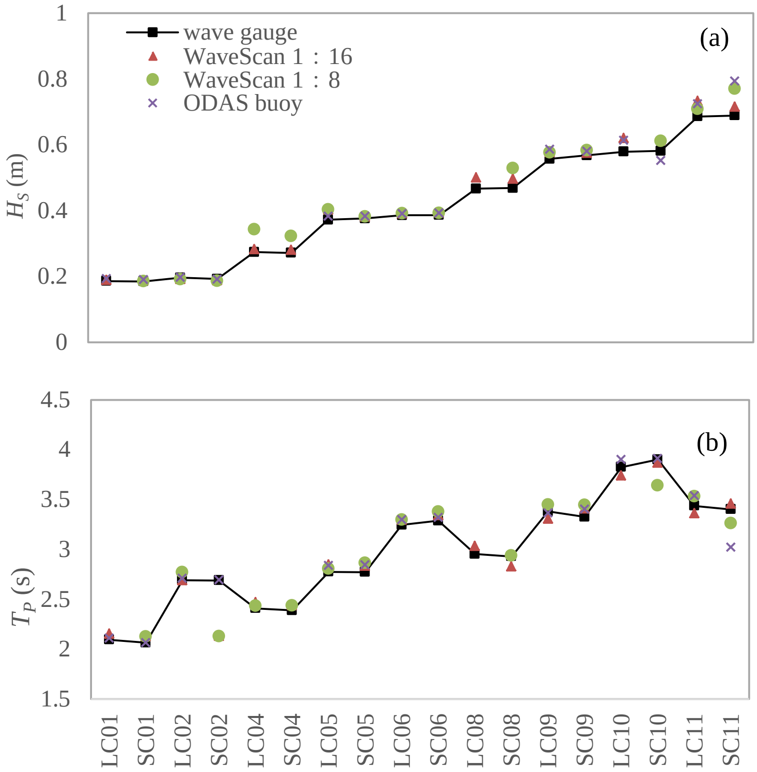

Figure 4 measurements for H_S (a) and T_P (b) during irregular wave states (LC/SC01-11)

4.3 Effect of the mooring system

In case the buoys were flushed too far away, the slack mooring lines were attached to the bottom of each buoy model. Contrast tests were set in irregular wave states for Wavescan 1:16 buoy model to check if the mooring system would affect the movements of the buoys. The wave density spectral characteristics recorded by the buoy model with mooring systems located at different depth are drawn together with those from the wave gauges, see Figure 5.

As the figures show, for the wave states with small wave heights, the measurements with different mooring systems seem quite close to each other. With the wave height getting larger, the buoy model with mooring system located at depth 10m tends to overestimate H_S and T_P, while the model in the other case shows very good agreement with wave gauges. For the extreme wave states such as SC10, the deeper mooring system shows the effect of amplifying the movements of the buoy model; besides, the movements of the buoy models weren't captured by the Qualysis system, as a result of the overreaction of the model during the extreme waves SC10/11.

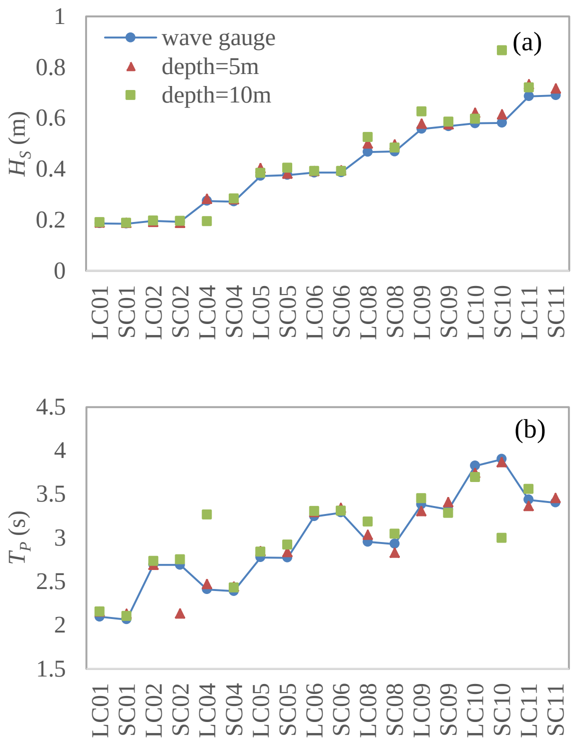

Figure 5 Measurements for H_S (a) and T_P (b) by 1:16 Wavescan buoy model with mooring system located at depth 5m and 10m during irregular waves

5 Conclusions

An experimental study was carried out on the performance of three wave buoy models, viz two Wavescan buoys and one ODAS buoy, in a wave tank using the European FP7 MARINET facilities. Wave tank tests were taken to investigate how the floating buoys act differently with each other and the fixed wave gauge on recording the wave surface information. Scaled models for ODAS buoy and Wavescan buoy were used with matching regular and irregular wave states. Zero-crossing method and FFT are used to analysis the data recorded by the measuring facilities.

The analysis results reveal that, for both regular and irregular waves, the Wavescan buoys have better performance than the ODAS buoy in terms of accuracy. It can also be seen that the wave characteristics of the Wavescan buoys have very good correlation with those of the wave gauges. Compared with the 1:8 Wavescan buoy model, the smaller one shows better performance on measuring the wave surface with less data missing and smaller errors. The smaller Wavescan buoy shows the smallest errors, which means the smaller Wavescan model is the best buoy model at recording the motions of water particle than the other two.

From the wave characteristics calculated, the buoys would underestimate or overestimate the peak period significantly for the very extreme irregular waves. Besides, the deeper mooring system affects the measurement significantly during some extreme states.

More physical tests and numerical simulations need to done to give a thorough analysis on the wave measurements using wave buoys. The effects of the dimensions of the buoys will be shown distinctive if more models can be investigated.

Acknowledgements

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References

[1] Barstow S, Ueland G, Krogstad H E, et al. The Wavescan second generation directional wave buoy [J]. *Oceanic Engineering, IEEE Journal of*, 1991, 16(3): 254-266.

[2] Smith G, Bittencourt-Ferreira C, Smith H. Protocols for the equitable assessment of marine energy converters [M]. Institute for Energy Systems, School of Engineering, University of Edinburgh, 2011.

[3] Smith H, Haverson D, Smith G H. A wave energy resource assessment case study: Review, analysis and lessons learnt [J]. *Renewable Energy*, 2013, 60: 510-521.

[4] Reguero B G, Menéndez M, Méndez F J, *et al*. A global ocean wave (GOW) calibrated reanalysis from 1948 onwards [J]. *Coastal Engineering*, 2012, 65: 38-55.

[5] Bendfeld J, Ditscherlein R, Splett M, et al. ADCP and Waverider Measurements for O&M at offshore windfarm locations[J].

[6] Pandian P K, Emmanuel O, Ruscoe J P, et al. An overview of recent technologies on wave and current measurement in coastal and marine applications [J]. *Journal of Oceanography and Marine Science*, 2010, 1(1): 001-010.

[7] Krogstad H E, Wolf J, Thompson S P, et al. Methods for intercomparison of wave measurements[J]. *Coastal Engineering*, 1999, 37(3): 235-257.

[8] Rademakers P J. Waverider-wavestaff comparison [J]. *Ocean engineering*, 1993, 20(2): 187-193.

[9] Allender J, Audunson T, Barstow S F, *et al*. The WADIC project: A comprehensive field evaluation of directional wave instrumentation [J]. *Ocean engineering*, 1989, 16(5): 505-536.