Uncertainty of motion tracking system used in a floating wave energy converter model study.

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Abstract—**Blue economy CRC deployed a four-float M4 (Moored Multi-Mode Multibody) device to demonstrate the potential of wave energy converters (WECs) for the Australian coast. An experimental study on a 1:15 scale model of the same device was performed in the Model Test Basin of the Australian Maritime College, investigating performance and behaviour, to aid in minimising the risks associated with open sea deployment. In model testing, the uncertainties of instruments and measurements directly affect the reliability of the results. Uncertainty analysis (UA) of WEC model studies is particularly important as it involves complex geometries, large motions and non-linear interactions. During the M4 experiment, the Qualisys motion tracking system was used to evaluate the hinge motion of the device, which is directly associated with the power capture. This paper discusses the details of an experimental investigation to precisely evaluate the uncertainties of this Qualisys motion tracking system. A calibration rig was designed to give known accurate motions to Qualisys marker arrangements, same as in the M4 model. The deviation in motion measured by Qualisys system was evaluated to better estimate the uncertainties of the system. It was noticed that there was a phase lag in other instruments with respect to Qualisys, which was unexpected. This phase lag can cause uncertainties, especially for WEC studies when measurements from different instruments are used in calculating power and this phase difference needs to be considered in the UA of the M4 model study. The conclusions from this study can be used in UA and future WEC model studies, improving the quality of the experiments.**

Keywords— **Laboratory experiments, motion response, uncertainty analysis, wave energy converters.**

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I. Introduction

Deploying wave energy converters (WECs) in the open ocean is a high-risk, high-investment endeavour. It is crucial to have full confidence in the performance of these technologies before they are deployed in an uncontrollable environment such as the open ocean. To understand their performance and behaviour, these devices are developed following the engineering approach of technology readiness level (TRL) where testing, validation and optimisation are conducted on a small-scale model before progressing to higher TRLs. The Ocean Energy Systems (OES) report [1] discusses the TRL approach suited for wave energy technologies. The approach comprises five stages with the size and scale of testing increasing as the technology progresses through each stage. If the results of the model studies were presented with an uncertainty value, developers can design the next TRL considering these error margins. This paper discusses an experimental study conducted to determine the uncertainty of a measurement system used on a WEC model study which can be later used to present the overall uncertainty.

Blue Economy CRC intends to promote marine innovation with the deployment of a WEC off the coast of Albany, Western Australia, as part of their research program. This deployment will demonstrate the potential benefits of the device for the local community. A 1:15 scale model (TRL 3) of the M4 (Moored Multi-Mode Multibody) WEC, was experimentally studied in the model test basin facility of the Australian Maritime College (AMC). Interested readers may refer to Howe et al. [2] for details of this model study and Kurniawan et al. [3] for insight on the deployment site. Model studies involve random and systematic errors which propagate to influence the results, causing uncertainties in measured performance. In the case of this M4 model study, it was expected that the Qualisys motion tracking system used for measuring motions might have the highest contribution to uncertainties. This is because measurements from Qualisys system is related to the power capture calculations, and it was noted that occasional discontinuities and noise in the recordings especially when the system momentarily loses track of the reflective markers. Such measurements needed to be further reprocessed in the Qualisys Track Manager (QTM) software to improve the quality.

Qualisys motion tracking is widely utilized in various fields of arts (animation, filmmaking) and engineering (robotics, automotive, biophysics). It tracks the motion of rigid bodies by sending infrared light to illuminate markers fixed on the body. The cameras then track these markers to calculate motion in six degrees of freedom (6-DOF) such as surge, sway, heave, roll, pitch and yaw. The non-contact nature of Qualisys makes it suitable for complex and sensitive experiments. For motions within a small volume of space, the Qualisys system is calibrated using a calibration wand of known length. The wand is illuminated and moved throughout the space of measurement and the QTM software builds a 3-D volume of the illuminated space [4]. The software provides the standard deviation of the captured wand length which can be used as the uncertainty value [5]. However, for larger volumes such as the model test basin at the AMC, the system is calibrated using fixed calibrations markers on the wave basin wall. This calibration method does not provide a standard deviation. Hence alternative method was needed to estimate uncertainties such as an experimental investigation.

Qie et al. [6] proposed a method for estimating the uncertainty of the Qualisys system by capturing 6- DOF data for 15 s before activating the wave maker. This data was filtered and the difference between the raw and filtered data was used to calculate the noise. However, such recordings were not taken during the M4 experiments. To estimate uncertainties, a comparison of the Qualisys data and measurements with another known measurement system is needed. Carter et al. [7] estimated the reliability of Oqus Qualisys camera by comparing the static position of markers at different known lengths and angles and with angular motion at a constant speed of 67° per second. The authors concluded that the Oqus cameras were reliable, and the uncertainties were small. It is important to note that the uncertainty of the Qualisys system depends on various parameters like camera positions, marker size, arrangement and QTM software error limits. Therefore, conclusions from one study cannot be directly applied on a different experiment and uncertainty analysis should be performed individually depending on the specific laboratory setup.

This paper presents the experimental study to estimate uncertainties by comparing measurements from Qualisys motion tracking system to measurements with a different instrument with less uncertainty. This study was carried out in an empty basin without water. However, in hydrodynamic model studies, water can reflect light causing the software to sometimes track a reflection instead of actual markers. The QTM software settings and camera positions can be adjusted to minimise the effect of reflections; hence influence of water is not considered for this study.

II. Methodology

A calibration rig was designed to apply known motion to a frame fitted with Qualisys markers. The displacement of the frame was measured using a Linear Variable Differential Transducer (LVDT) and its angular motion was measured using a digital encoder. The 6-DOF data of the same frame was recorded using the Qualisys system and compared with the LVDT and encoder data to estimate uncertainties. The subsequent sections describe the details of the calibration rig used for this study, the test conditions and sensors used for comparing measurements.

A. *Calibration rig*

The primary component of the calibration rig is a frame designed to replicate the marker placement used in the original hydrodynamic test [2]. Eight Qualisys markers were used in the original model: four for tracking the motion of components forward of the mid-floats (hereafter referred to as the forward body) and the remaining four markers for tracking the motion of the model aft of the mid-floats (referred to as aft body). Fig. 1 illustrates the frame with the marker arrangement for both the aft and forward bodies alongside the actual model showing the same configuration.

The Qualisys system requires at least one marker at a different height from the remaining markers to facilitate more accurate tracking and rotation calculations by defining an XYZ reference plane. In this setup, the centreline markers were positioned at the same height, while the two side markers were also placed at a uniform but different height. The forward body was assembled with 40 mm diameter marker balls, whereas the aft body markers had a diameter of 50 mm. The calibration rig also included an LVDT to measure the displacement and an angular encoder to measure the angles. The marker body was mounted on a slider block driven by a servo motor to apply known displacements. Fig 2 shows the schematic and the actual calibration rig.

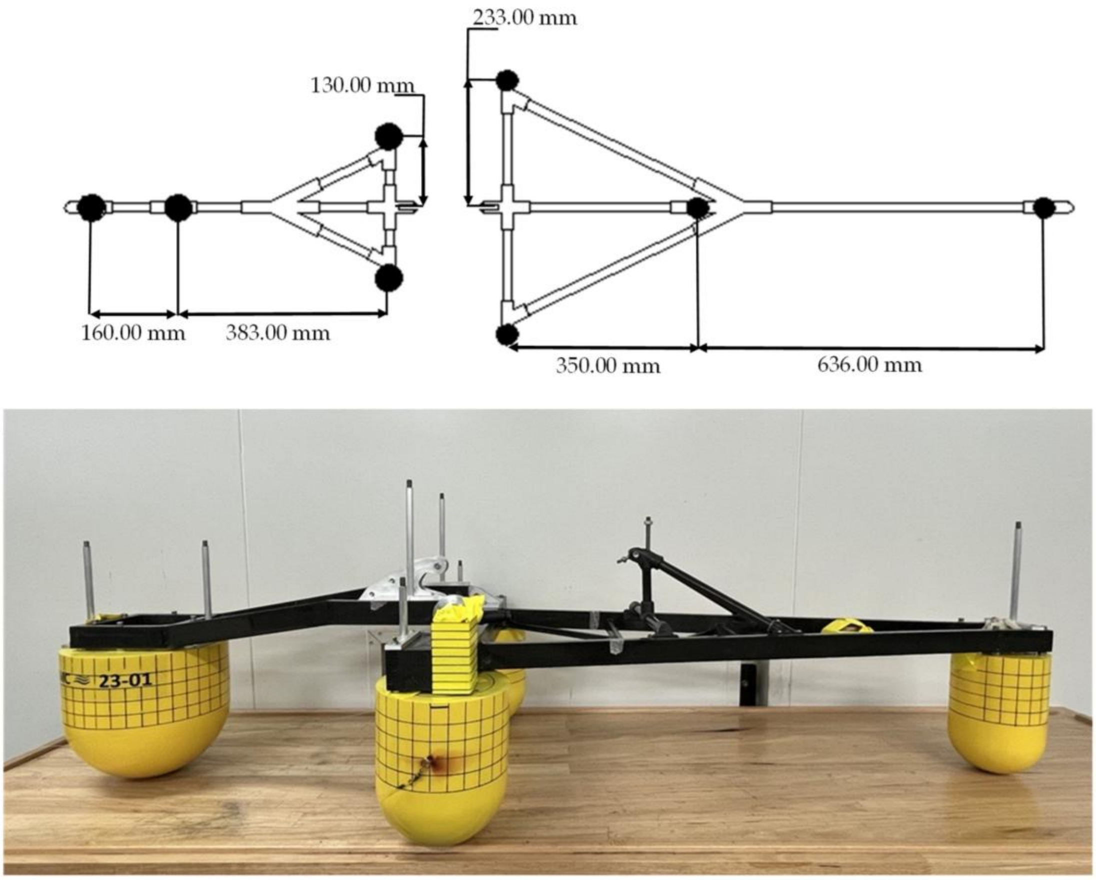


Fig. 1. Top picture shows the schematics of the marker frame for aft body and forward body respectively. Bottom picture shows the actual M4 model, Qualisys markers were fixed on the steel rods seen in the model.

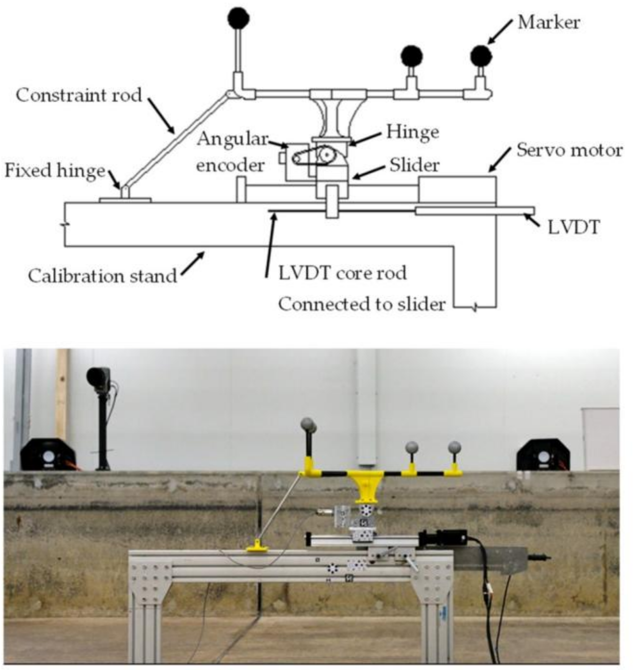
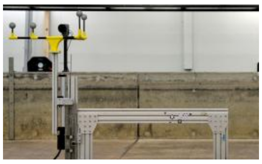
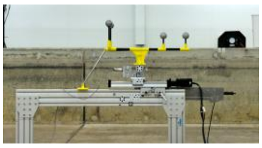


Fig. 2. Schematic of calibration rig on top and the actual calibration rig in model test basin. The rig is shown for surge-pitch coupled motion with aft body markers. One Qualisys camera and two fixed calibration markers can also be seen on the wall behind the rig.

B. *Experimental test matrix*

During the hydrodynamic experiments, the M4 model was tested with a tether mooring attached to the mid-floats using a bridle, in addition to a main mooring line attached to the forward float. This setup ensured that the model was always heading to the incoming wave resulting in minimal sway and yaw motions. The 1-2-1 arrangement of floats (one at the bow, two at the mid and one at the stern) also contributed to model stability, leading to minimal roll. Therefore, the degrees of freedom (DOFs) of motion in order of importance were pitch, heave, surge, sway, roll and yaw. Pitch was prioritized due to its direct influence on power capture, estimated from the hinge angle derived from the relative pitch between the aft and forward bodies. Coupled surge-pitch and heave-pitch motions were also tested to assess uncertainty under multi-modal conditions, reflecting the coupled dynamics typical in wave environments. However, this study was limited to two-degree coupling, whereas real hydrodynamic scenarios may involve three or more DOFs. Motions in sway, roll, and yaw were not included in this study, as they are secondary DOFs, but may be explored in future work. Table I shows the different configurations of the rig for each test condition.

TABLE I
TEST MATRIX FOR UNCERTAINTY STUDY

Test conditions	Rig setup	Description
Surge		The frame attached directly to the slider.
Heave		Slider and LVDT was mounted vertically.
Pitch		The frame fixed on the rig with hinge and encoder, constraint rod engaged and was made to move along the slider.
Surge-pitch		Constraint rod engaged if fixed on rig and frame was made to move along the slider.
Heave – pitch		Same as Surge pitch condition but the slider and LVDT was mounted vertically.

Stroke (mm) and period (s) values were input into the position controller software which then prompted the motor to generate sinusoidal displacements of the slider. Here stroke refers to the peak-to-peak displacement of the slider. Table II presents the test matrix for this study, with all the test runs carried out at least three times. The stroke values were selected to observe differences in uncertainty across small, medium and high amplitude relative to the maximum motion of the M4 model. The oscillation periods were selected such that 0.70 s, 0.80 s, 1.00 s, and 1.79 s represented regular wave periods, while 1.35 s and 1.54 s corresponded to the peak periods of significant operational sea states. Due to peak acceleration and velocity limitations of the linear motor, strokes greater than 60 mm could not be generated for periods of 1.35 s, 1.54 s, and 1.79 s. Periods exceeding 0.8 s were avoided for the 5 mm stroke because, under such conditions, the rate of displacements was lower than the resolution of the LVDT, leading to high noise in the data. The use of signal processing filters to remove noise can introduce more uncertainty due to phase shifts or distortion [8]

TABLE II
TEST MATRIX FOR UNCERTAINTY STUDY

Degree of freedom	Stroke (mm)	Period (s)
Surge	5	0.7, 0.8
	10	1, 1.35, 1.54, 1.79
	50	0.7, 0.8, 1, 1.35, 1.54, 1.79
	100	1.35, 1.54, 1.79
Heave	10,30,50	0.7, 0.8, 1, 1.35, 1.54, 1.79
Pitch	5	0.7, 0.8 ,1.54, 1.79
	10, 40	0.7, 0.8, 1, 1.35, 1.54, 1.79
	100	1.35, 1.54, 1.79
Surge - pitch	5	0.7, 0.8
	10	1, 1.35, 1.54, 1.79
	50	0.7, 0.8, 1, 1.35, 1.54, 1.79
	100	1.35, 1.54, 1.79
Heave - pitch (Forward body)	10,40	0.7, 0.8, 1, 1.35, 1.54, 1.79
	100	1.35, 1.54, 1.79
Heave – pitch (Aft body)	10,40	0.7, 0.8, 1, 1.35, 1.54, 1.79
	60	1.35, 1.54, 1.79

C. *Sensor and calibration*

The calibration rig was equipped with a DC-EC 5000 series LVDT from Measurement Specialties Inc. (MEAS), capable of measuring displacements up to ± 125 mm. This sensor was calibrated prior to the experiment by applying known displacements and recording the corresponding output voltage. The Type B uncertainty of the LVDT is calculated using the standard error of estimate (SEE) from the calibration as discussed in [9]:

$$SEE = \sqrt{\frac{\sum(y-\hat{y})^2}{M-2}} \quad (1)$$

where M is the number of data points and $y-\hat{y}$ is the difference between the measured value and the linearly fitted value. The Type B uncertainty of the LVDT, estimated from the SEE of the calibration was ± 0.39 mm. Uncertainties are usually categorised as Type A and Type B [10] based on the method of evaluation. Type A refers to uncertainties evaluated statistically from repetitions while Type B are those evaluated non-statistically such as from calibrations, previous knowledge or datasheets.

For measuring angles, a DFS60 series incremental encoder from Sick Sensor Intelligence was used. This digital sensor does not require additional calibration. Type B uncertainty of the encoder, as specified by manufacture in specifications is ± 0.05 °. The LVDT and encoder were connected to a National Instruments Data Acquisition system (NI-DAQ).

The Qualisys system uses Oqus 700+ series tracking cameras, and the system was calibrated using fixed calibration markers on the basin wall. After calibration, the Qualisys software capture the markers on the rigid body to construct a skeleton connecting all tracking markers. The local origin of the rigid body can be defined in the software and is typically set at its centre of gravity. The quality of motion tracking can be improved by adjusting software parameters, such as bone length tolerance. This parameter defines the maximum allowable difference (in mm) between the actual and tracked distances between markers. In addition to bone tolerance, parameters such as prediction error, maximum residual, minimum number of frames per trajectory and minimum ray count per marker can also improve the quality of tracking. Prediction error represents the maximum difference (in mm) between the mathematically calculated subsequent position of a trajectory and the captured point assigned to the trajectory. The maximum residual is the distance (in mm) from the 3D point within which all intersecting light rays are considered part of that point. All software settings were optimised to best suit the marker size and arrangement, thereby minimising noise and uncertainty in the recorded data.

III. RESULTS AND DISCUSSION

The displacement and pitch angles measured by the Qualisys system were compared to those obtained from the LVDT and encoder, respectively. However, the displacement measured during the coupled conditions could not be directly compared with the LVDT. The Qualisys system tracks the position of the local coordinate of the rigid body, which was set to match that of the original M4 model and differs from the position of the slider block. The position vectors tracked by the system needed to be translated to a point which is vertically aligned with the slider block. The position vectors were translated to the coordinate of the hinge point using a rotational matrix as discussed in the QTM software manual [4]. The translation of position vectors can be written as:

$$\begin{bmatrix} X^T \\ Z^T \end{bmatrix} = \begin{bmatrix} X \\ Z \end{bmatrix} - \begin{bmatrix} X' \\ Z' \end{bmatrix} + \begin{bmatrix} Cos\theta & Sin\theta \\ -Sin\theta & Cos\theta \end{bmatrix} \begin{bmatrix} X' \\ Z' \end{bmatrix} \tag{2}$$

Here X^T, Z^T are the translated position vectors, X, Z are the recorded position vectors; X', Z' are the horizontal and vertical distance, respectively, between the local origin and

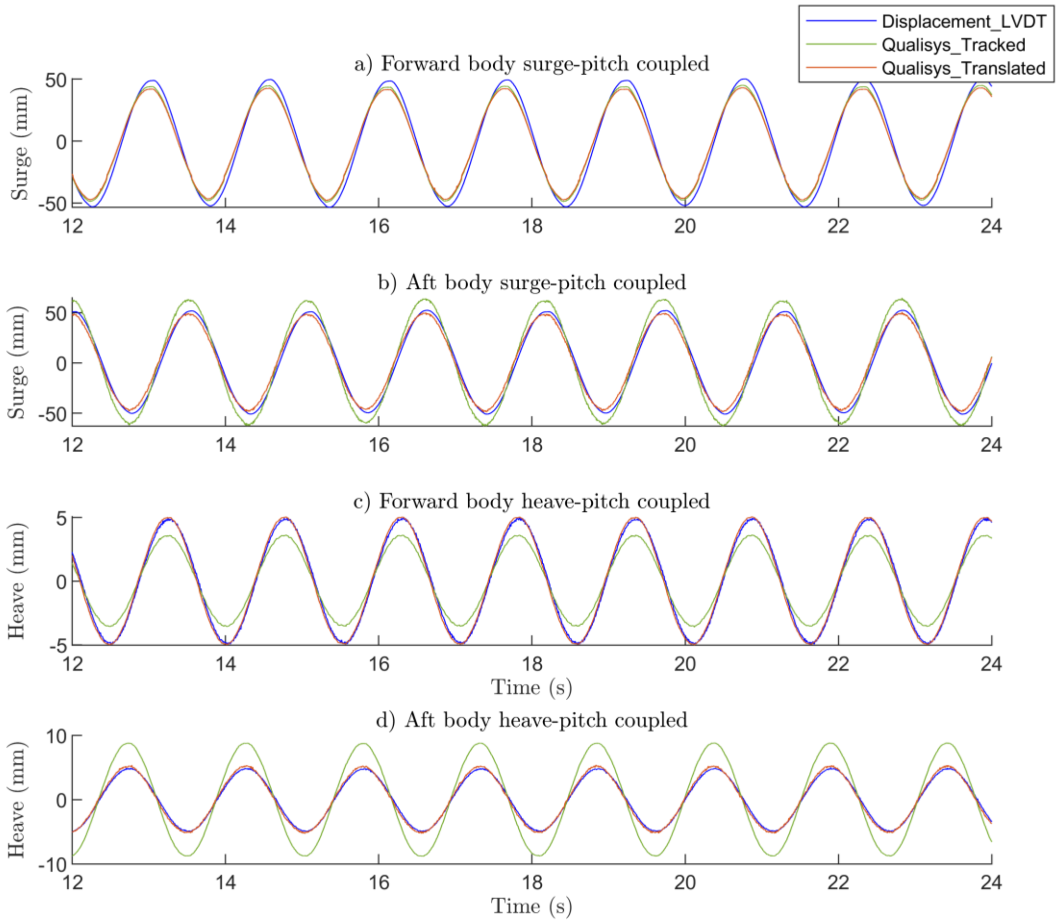


Fig. 3. Timeseries of the comparison of displacements measured by LVDT, tracked by Qualisys and translated to the hinge point for a) surge displacement from surge-pitch and b) Heave displacement from heave-pitch coupled test.

the hinge point (the point to which the vectors are translated) and θ is the pitch angle. Fig. 3 shows the time series of translated surge and heave vectors compared to the tracked and LVDT measurement

The residuals, or the difference between the measurement by Qualisys system and contact sensors were estimated at all data points:

$$Residual = x_{Qualisys} - x_{LVDT/Encoder} \quad (3)$$

Here, $x_{Qualisys}$ is the displacement or angle from Qualisys and $x_{LVDT/Encoder}$ is the measurement from LVDT or encoder respectively. To simplify presentation and condense the data, phase averaging was applied to the time series. Phase averaging gives an averaged representation of data points with the same phase overlaid on top of each other, here phase is determined as:

$$Phase = Remainder\left(\frac{t}{T}\right) \quad (4)$$

Here t is timestep and T is period. Phase averaged data were calculated by dividing one period into a discrete number of bins and computing the average of all datapoints within each bin. This method simplifies the presentation of time series data and provides insight into the phase-dependent behaviour of data. More information about phase averaging can be found in Orphin et al. [11]. Fig. 4 shows an example of a Qualisys-measured pitch angle compared to the encoder angle along with the residuals and corresponding phase averaged data.

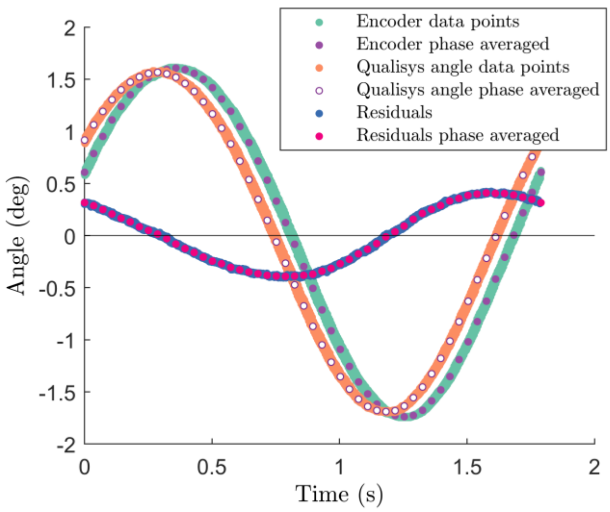


Fig. 4. Comparison of the Qualisys angle and encoder angle with residuals for forward body surge pitch coupled test condition with stroke 50 mm and period 1.79 s. The data points marker may appear as line as data at each timestep with similar phase from a timeseries of 45 s is presented here.

These phase averaged plots revealed presence of a time lag between the encoder and the Qualisys data. This phase difference was unexpected as data acquisition system and Qualisys system were triggered simultaneously. Ideally, any delay among the data systems should be unobservable or within a timestep. As an initial approach, the phase lag of all the collected data was further analysed by comparing the zero-up crossing time. The phase correction minimises the residuals, so a robust phase correction method was developed using the fminbnd function of MATLAB (version 2023a was used) to find the required time shift in data to obtain minimum residuals. Fig. 5 shows the phase difference among the data for all the runs. Even though the phase difference varies slightly among the runs, the average for each period remained consistent. The Qualisys data leads the LVDT data by an average of 0.02 s while the encoder lags by an average of 0.078 s. The phase shift was initially assumed to result from the triggering mechanism between the two data systems. However, expert opinion later suggested that the phase difference in the LVDT data may be caused by filtering and signal processing within the DAQ system. The encoder stored a small set of junk data at the beginning of recordings, which resulted in higher phase lag in this sensor data.

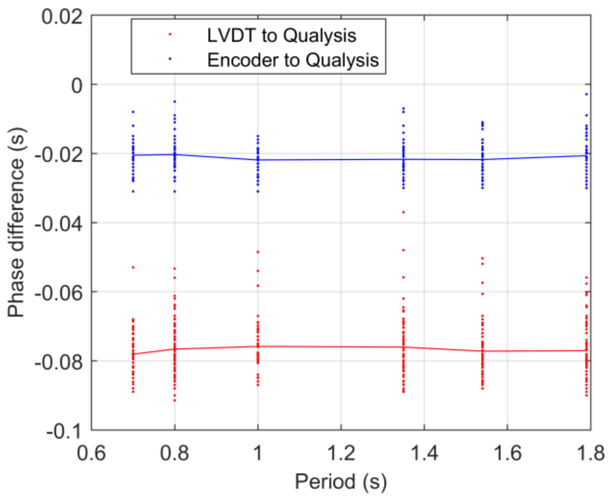


Fig 5. Phase difference among Qualisys, encoder and LVDT for all the tested runs. Here the blue and red line represents the average of the corresponding phase difference of the runs with the same period.

The data signals were post-processed for phase correction relative to LVDT signal and these post processed signals were compared for residuals. (The LVDT signal was chosen arbitrarily, as the focus was solely on residuals) Fig. 6 shows the same angular data presented earlier, now corrected for phase. The overall magnitude of the residuals decreased, indicating that phase correction was needed for accurate residual analysis. It can also be observed that the region of maximum residuals shifted from the zero crossing points to the regions near the peaks, where the rate of displacement was changing.

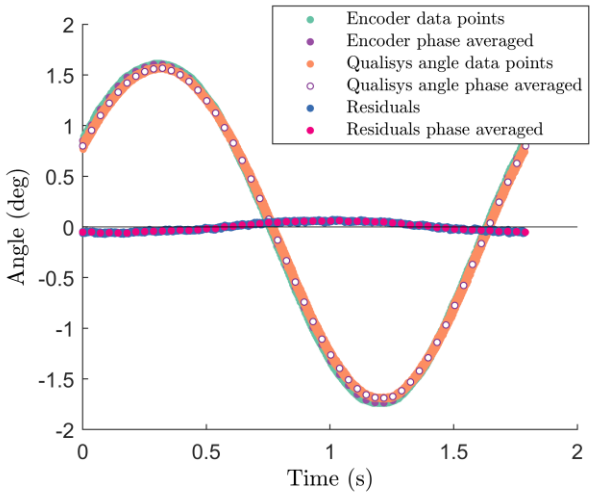


Fig. 6. Comparison of the Qualisys angle and encoder angle after phase correction from forward body surge-pitch coupled test condition with stroke 50 mm and period 1.79 s.

In tests focusing solely on displacement, it was observed that the magnitude of residuals was smaller than angular residuals. Fig. 7 shows the results of the surge displacement alone. The region of maximum residuals cannot be generalised, as for some runs it occurred near the peak while for others it was near the zero-crossing. This occurrence of maximum residuals at the zero-crossing region may be due to small phase shift which cannot be removed.

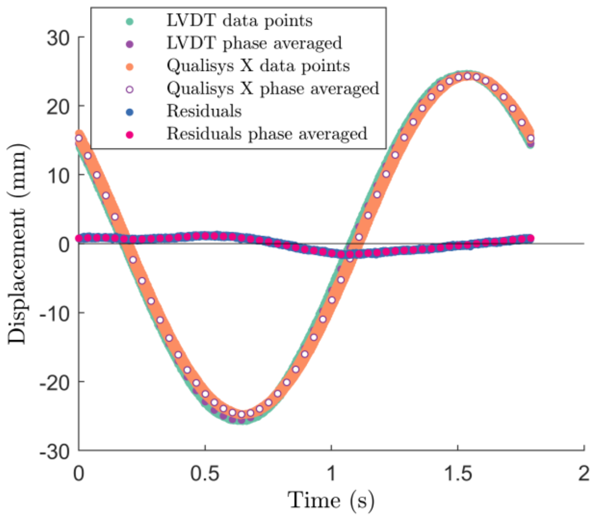


Fig 7. Comparison of the Qualisys displacement to LVDT measurements with residuals for surge only test with stroke 50 mm and period 1.79 s

Generally, phase difference is of least importance for hydrodynamic studies as only the magnitude of measurements was used. However, for wave energy converter studies, the phase information is important, as power estimation uses measurements from two measuring systems namely force measured by a load cell and motions measured by Qualisys. The load cell and LVDT use the same DAQ system and similar signal processing, so it is possible that the same kind of phase difference was present in the M4 model study. Any phase difference between the measuring systems can cause uncertainties in power estimation.

The Fig. 7 shows the distribution of residuals from a pitch angle before and after phase correction. As the distribution is centred around zero, the standard deviation (Std.D) of the residuals gives the uncertainty in the measurement. It can be noted that after phase correction, the residual values are mostly near zero indicating good agreement between the measurements while before phase correction the residual values were widely distributed. Table 3 compares the average standard deviation value as well as the percentage of standard deviation for all tested conditions, before and after phase reduction. The uncertainty is less than or equal to 5 percent for all degrees of freedom, indicating that the measurement systems are precise if no phase difference is present. The relatively higher percentage of uncertainty in the displacement measurements of the surge-pitch coupled condition is caused by the involvement of both position and angular measurements during translation of vectors.

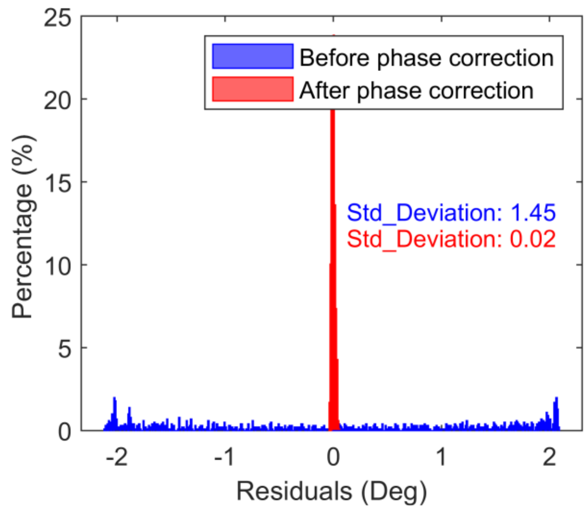


Fig 8. Histogram distribution of the residual values for a comparison of pitch angles. Histogram made with bin width of 0.01

TABLE III
UNCERTAINTY IN THE DIFFERENT EACH TEST CONDITION

Degree of freedom	Before phase correction		After phase correction	
	Std.D	Std.D (%)	Std.D	Std.D (%)
		Aft Body		
Surge (mm)	1.854	5.01	0.449	1.911
Heave (mm)	1.275	2.45	0.189	0.808
Surge-Pitch (mm)	4.253	8.980	1.256	4.487
Heave-Pitch (mm)	8.327	6.942	0.552	2.512
Pitch (deg)	1.067	1.460	0.015	0.324
Pitch-Surge (deg)	0.668	9.807	0.192	4.880
Pitch-Heave (deg)	0.769	3.849	0.031	0.843
		Forward Body		
Surge (mm)	1.803	4.443	0.335	1.022
Heave (mm)	1.049	4.164	0.155	0.700
Surge-Pitch (mm)	2.224	6.065	1.921	5.092
Heave-Pitch (mm)	3.862	10.215	0.226	0.947
Pitch (deg)	0.805	17.324	0.014	0.297
Pitch-Surge (deg)	0.370	15.570	0.025	1.095
Pitch-Heave (deg)	0.491	13.368	0.020	0.573

For coupled cases (e.g. Surge-Pitch) first term refers to the compared degree and second term is the coupling.

In hydrodynamic experiments, the averaged magnitudes are of primary interest; therefore, it is important to assess any deviations in peak or amplitude values. The amplitude of each measurement was calculated as half the difference between the phase averaged crests and troughs. The difference in amplitude between measurements was estimated as:

$$Difference = A_{Qualisys} - A_{DAQ} \tag{5}$$

Here $A_{Qualisys}$ is the amplitude of displacement or pitch angle measured by Qualisys and A_{DAQ} is the amplitude of the displacements or angle measured by LVDT or encoder, respectively. Fig. 9 shows the difference in amplitude of displacements. For the surge-only condition, the amplitude discrepancies were below 0.96 mm for the forward body and 0.68 mm for the aft part. In the case of heave alone, the differences remained minimal peaking at 0.43 mm for the forward body and 0.34 mm for the aft body. Notably, the highest difference 26 % was observed for a 2.5 mm amplitude surge displacement, while this was less than 3.6 % for the heave alone case.

Surge and heave amplitude in the coupled conditions exhibited higher variation. This is attributed to the fact that translating the position vector incorporates uncertainties from the angle measurements. The maximum surge deviation in the surge-pitch coupled tests was 6.44 mm for forward and 3.22 mm for the aft body. In terms of percentage deviation, the aft body had higher deviation especially for smaller amplitude motions. The highest deviation was 46 % for the aft body this may be caused by the presence of noise in the tracked signals. The smaller separation between markers on the aft body may lead to a phenomenon known as marker shadowing. This occurs when one marker obstructs the reflected rays from another marker and can induce noise into the tracking. For the heave-pitch coupled condition, the aft body also had higher percentage of deviation of 36 % again likely due to marker shadowing. The maximum percentage of deviation for the forward body was only 15 % for surge-pitch coupled and 3.4 % for the heave pitch coupled condition.

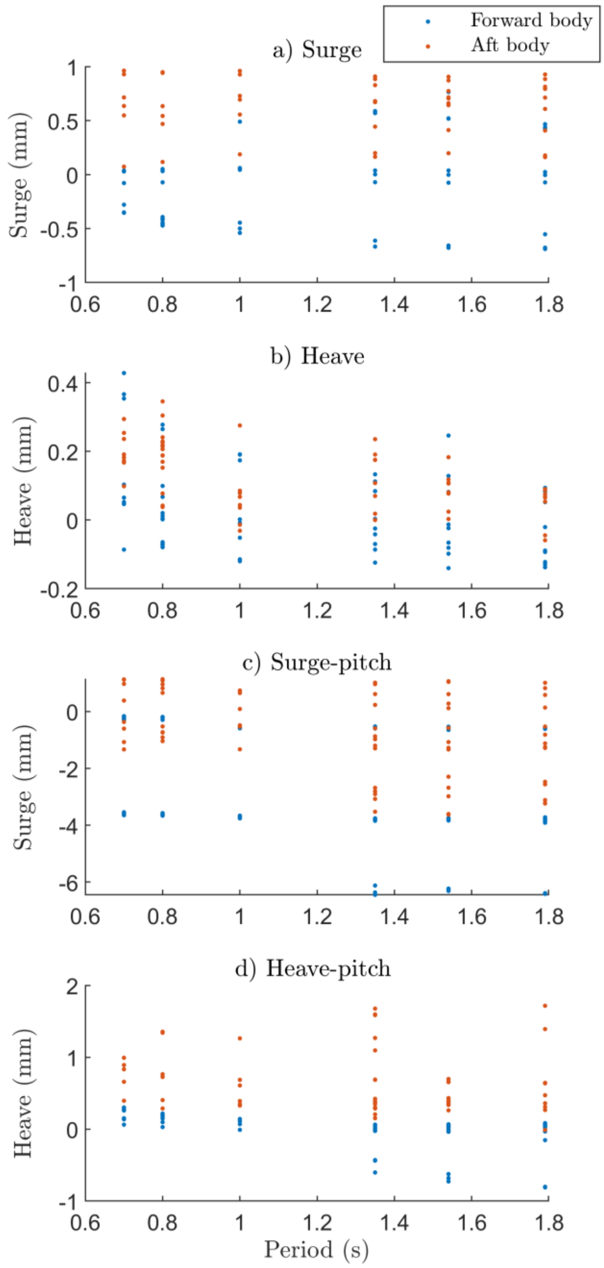


Fig. 9. Difference in amplitude of displacement for a) Surge b) Heave c) Surge-pitch and d) Heave-pitch coupled motions.

The amplitude of the pitch angle tracked by Qualisys compared to the encoder measurement is depicted in Fig 10. The highest angular amplitude difference for the forward body was observed during the heave-pitch coupled motion (0.1°), while for the aft body, it occurred during the surge-pitch coupled motion, where the Qualisys-measured amplitude was 0.59° less than that recorded by the encoder. The maximum percentage difference is 15 % for a relatively small amplitude angular motion of 0.29 °. Except for the condition of surge-pitch coupled motion of aft body, the percentage deviation for all the angle measurements were less than 5 %. This indicates a high level of accuracy in most measurements. There were instances when the aft body markers had to be recaptured as the software lost tracking of the markers. This recapturing process may have improved the accuracy of the heave- pitch coupled motion compared to the surge pitch conditions.

During the experiments, several observations were made which are likely to have contributed to the uncertainties. One such observation was that a 50 mm diameter pipe fixed in the basin obstructed one of the forward body markers from a tracking camera during strokes of 100 mm or more. The recorded data for such runs were continuous but with a small jump at that instance. Therefore, care should be taken to remove any obstructions to avoid undetectable undulations in data. Another observation was that, sometimes when the QTM software settings were not optimised for the motions being studied, the Qualisys system occasionally tracked the body with significant noise. The defined rigid body would sometimes appear to bounce or display a missing marker. In such cases, tracking was observed to overestimate motions by up to 94%. It is recommended that software settings be adjusted if the markers appear differently from their initial capture, or that the rigid body markers be recaptured to minimise uncertainties. The Qualisys system offers the advantage of allowing data to be reprocessed at any time by adjusting uncertainty parameters such as prediction error, maximum residual, and bone length tolerance. This enables reprocessing of data with higher uncertainties using different parameter sets to improve measurement accuracy. In future work, a sensitivity analysis of these parameters will be conducted to determine whether they are related to the motion period or marker arrangement.

IV. CONCLUSION AND FUTURE WORK

An experimental comparison was conducted between the Qualisys motion tracking system and contact sensors such an LVDT and angular encoder, aiming at evaluating the level of uncertainties in the Qualisys measurement system. This experiment was part of a PhD research project focusing on investigating uncertainties in the model study of a floating multibody WEC. In the hydrodynamic experimentation of this WEC, the Qualisys motion tracking system was used to measure motions in measuring in 6 DOF and to estimate the hinge angle from the relative pitching between the aft and forward bodies. The preliminary analysis yielded the following findings:

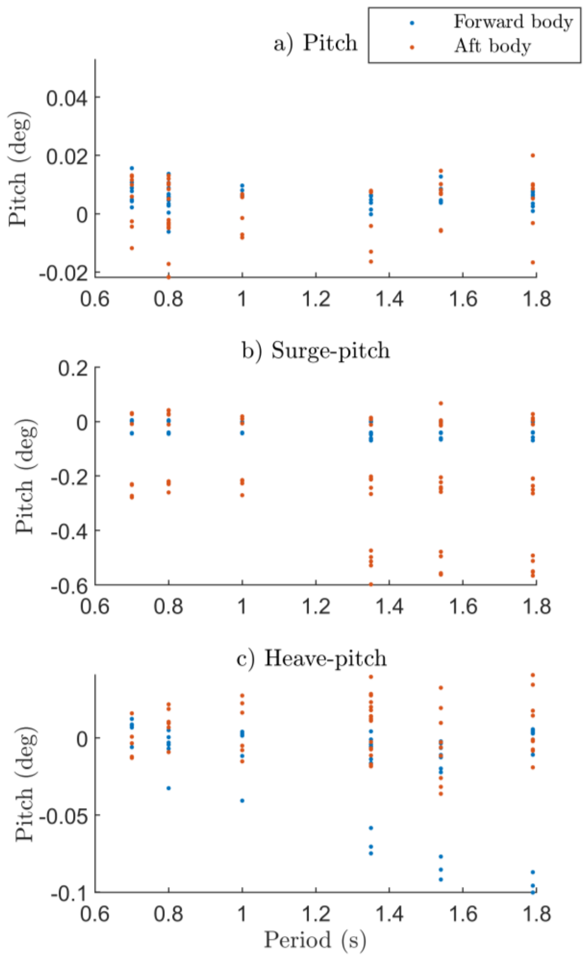


Fig. 10. Difference in amplitude of pitch angle for a) Pitch alone, b) Surge-pitch and c) Heave-pitch coupled motions.

- The phase lag was observed between datasets. This can introduce uncertainties in WEC experimental studies, as power estimation relies on synchronised data from multiple measuring systems.
- The Qualisys measurements are generally accurate, with minimal differences observed under most test conditions. Larger discrepancies in displacement during coupled motion tests were attributed to combined uncertainties in position vectors and angular measurements during coordinate translation.
- Adequate spacing between markers on the model is crucial to prevent marker shadowing. The forward body, which had better marker spacing exhibited less variation than the aft body.
- Uncertainty increases when Qualisys loses track of even a single marker. It is recommended to recapture the rigid body immediately upon detecting the loss of any marker. Although the system can continue recording with at least three markers, the resulting data may have higher uncertainty.

Further investigations will be carried out to identify the causes of this deviation in measurements. The presence of phase lag among the data was unexpected and this must be considered in the uncertainty analysis of the M4 model study.

As part of the Ph.D. research uncertainty analysis of the M4 WEC model will be conducted using Monte Carlo Method (MCM) of error propagation [12]. The conclusions from this experimental investigation will be included in the development of the MCM model and results of the hydrodynamic study of the M4 WEC with overall uncertainty values will be presented in future work.

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