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The Assessment of Water Surface Elevation Uncertainty in a Hydraulics Laboratory

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ABSTRACT: Physical model testing forms a critical part of the development process for offshore renewable energy (ORE) technologies. Devices and structures generally follow a Technology Readiness Level (TRL) development pathway which has nine steps ranging from the initial idea (TRL1) to commercialisation (TRL9). In ORE, technologies are tested extensively in laboratory environments up to TRL4 after which a decision is made as to whether a particular technology has sufficient potential to justify moving to open sea environments where the costs can be much higher. Therefore, physical model testing plays a critical role in the development process and in recent years increased emphasis has been placed on improving quality procedures and implementing best practice methodologies. The International Towing Tank Conference (ITTC) and the International Electrotechnical Commission (IEC) have been developing testing standards whilst European Union funded projects such as Equimar, MaRINET and MaRINET2 have been working with testing infrastructures in developing a more uniform approach to testing. However, a standardised approach to the assessment of uncertainty in physical testing has yet to emerge. This paper focuses on and estimates the variation associated with wave elevation measurements using conductive wave probes in a hydraulics laboratory, a key input in all physical testing analysis.

1. INTRODUCTION

With the installation of the 30MW Hywind pilot project in 2017 and the ongoing works on the 50MW Kincardine farm, Scotland, Floating Offshore Wind Turbines (FOWT) are now a commercial reality. However, many floating wind platform concepts are still progressing through the Technology Readiness Levels (TRLs) via a combination of experimental and physical testing, over 30 such concepts have been identified [1]. The progression of these technologies through the TRLs has resulted in wealth of fundamental research in the area of floating wind energy to support the advancement to commercialisation.

The systematic assessment of experimental uncertainty has only emerged in the past 15 years [2]. Guidelines are provided for the assessment of uncertainty in tank testing by both ASME [3] and the ITTC [4] with specific guidance provided by the ITTC [5] for the testing of offshore wind turbines. However, these do not provide a systemic approach to the assessment of experimental uncertainty or variation.

There have been several recent studies on developing output-only markers for monitoring scaled renewable energy device platforms [8-10], assessing control efficiency [11-13] and even understanding the variations of responses of such scaled structures for various sensors [14]. While these results are important in terms of establishing an experimental benchmark, their results are also fundamentally dependent on the variation and uncertainty of the wave heights generated in the basin. There have been some limited and excellent work around addressing this uncertainty and error [15-17], but there is still a need to experimentally expand this topic further due to the overall paucity of literature in this topic.

This paper takes this need of contributing to the experimental evidence base of such variation from wave basin tests and focuses on the assessment of uncertainty in the measurement of wave elevation using conductive wave probes during physical test campaigns. Accurate wave elevation data is vital for all analysis emanating from physical testing. The data used in this report are from an experimental campaign conducted in the Lir National Ocean Test Facility, in the ERI MaREI Centre, University College Cork. A total of six conductive waves probes were used to measure the water elevation. For each probe, a linear regression analysis has been investigated, as well as the uncertainty of the wave probe signal. The results are expected to be helpful for establishing better the Technological Readiness Levels (TRLs) of the various Offshore Renewable Energy (ORE) device concepts.

2. TEST CONDITIONS

2.1. Deep ocean basin specifications

The basin shown in Figure 1 below has dimension of 35 m long, 12 m wide and 3 m deep. The basin is equipped with 16 hinged force feedback paddle capable of a peak wave generation condition of the significant wave height Hs =0.6m, peak period Tp =2.7s and the maximum wave height Hmax =1.1m. The water depth can be adjusted thanks to movable floor until the maximum of 3m deep.

During the wave probe calibration, the paddles were stationary and the water depth was set at 750 mm to access to adjust the wave probe elevation.

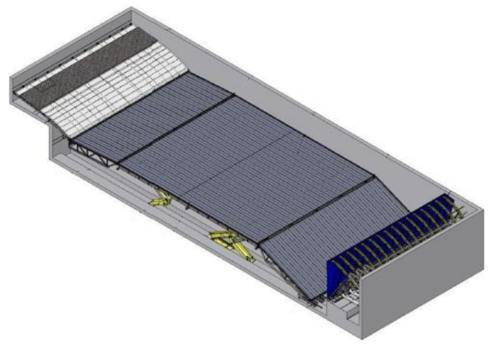

Figure 1: Schematic view of the Lir National Ocean Test Facility: Deep Ocean Basin

2.2. Wave probe specifications

The wave probes are resistance probes which output voltage which is directly related to the water surface elevation. During calibration the wave probes were spaced as per Table 1, the first wave probe (WP1) was closest to the paddles and the sixth (WP6) is the one nearest to the beach.

Table 1: Wave probe spacing for experiments.

Wave Probe	WP1	WP2	WP3	WP4	WP5	WP6
Distance to the WP1 (m)	0.00	0.15	0.28	0.57	1.16	2.44

2.3. Calibration

The calibration methodology for the wave probes consists of raising and lowering in still water at set elevations and recording the output voltage for each elevation. The elevations listed in Table 2 were used. For each wave probe, the voltage at each elevation were recorded. Having recorded these data, the linearity of the elevation to voltage relationships were assessed.

Table 2. Recorded elevations during a wave probe calibration.

Elevation recorded (mm)	0	-300	-200	-100	0	100

3. ANALYSIS METHODS

Figure 2 shows a typical signal recorded during a wave probe calibration. To determine the average value at a constant elevation, ranges were determined to calculate the mean voltage signal at each elevation.

In order to avoid errors, a period when the disturbances to the water surface elevation caused by the adjustment of the wave probes were selected. A minimum of 90 second was required to calculate the mean of the signal.

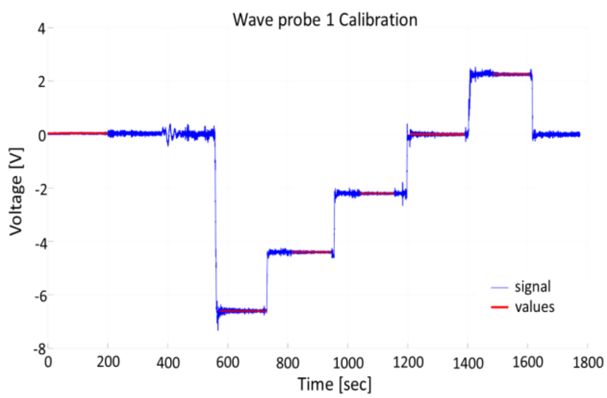

Figure 2: WP1 calibration signal

3.1. Linear regression analysis

With all mean values for each elevation for each probes, a linear regression was used to assess if the output elevation data of the probes are correct and follow a linear relationship with voltage. Figure 3 shows the average values of voltage for each elevation. With a representative linear equation for the elevation to voltage relationship, we now apply the by proposed methodology of the ITTC Procedure "Uncertainty analysis Instrument Calibration" in which a number of methods to assess uncertainties in regression analysis are proposed

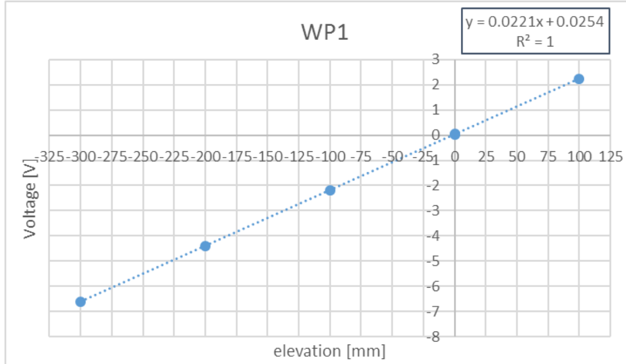

Figure 3: Linear regression on WP1

3.2. Uncertainty in noisy signal

The document "Measurements and their Uncertainties" from T.P.A. Hase and I.G Hughes shows how to determine uncertainty from a noisy signal as a function of time. The proposed method was implemented for the voltage signal of the wave probes and also the elevation measurements. This method consists on taking all the points in a range where the signal appears constant and calculating the 'time averaged mean' and standard deviation. The standard error (or uncertainty) is then the result of the standard deviation divided by the square root of the number of the sample:

$$\alpha = \frac{\sigma_{N-1}}{\sqrt{N}} \tag{1}$$

where α is the standard error (uncertainty), σ_{N-1} the standard deviation, N the number of samples. The results are best displayed as a histogram shown in Figure 4.

4. RESULTS

4.1. Linear regression analysis

All mean values determined are summarise in the following table, these values allow calculation of the correlation between elevation and voltage and the assessment of the quality of the correlation with the $R2$ value.

To compare the six wave probes, the correlations are plotted in Figure 5 where we can see that better agreement between probed for positive elevations.

Returning to the ITTC procedure "Uncertainty Analysis Instrument Calibration",

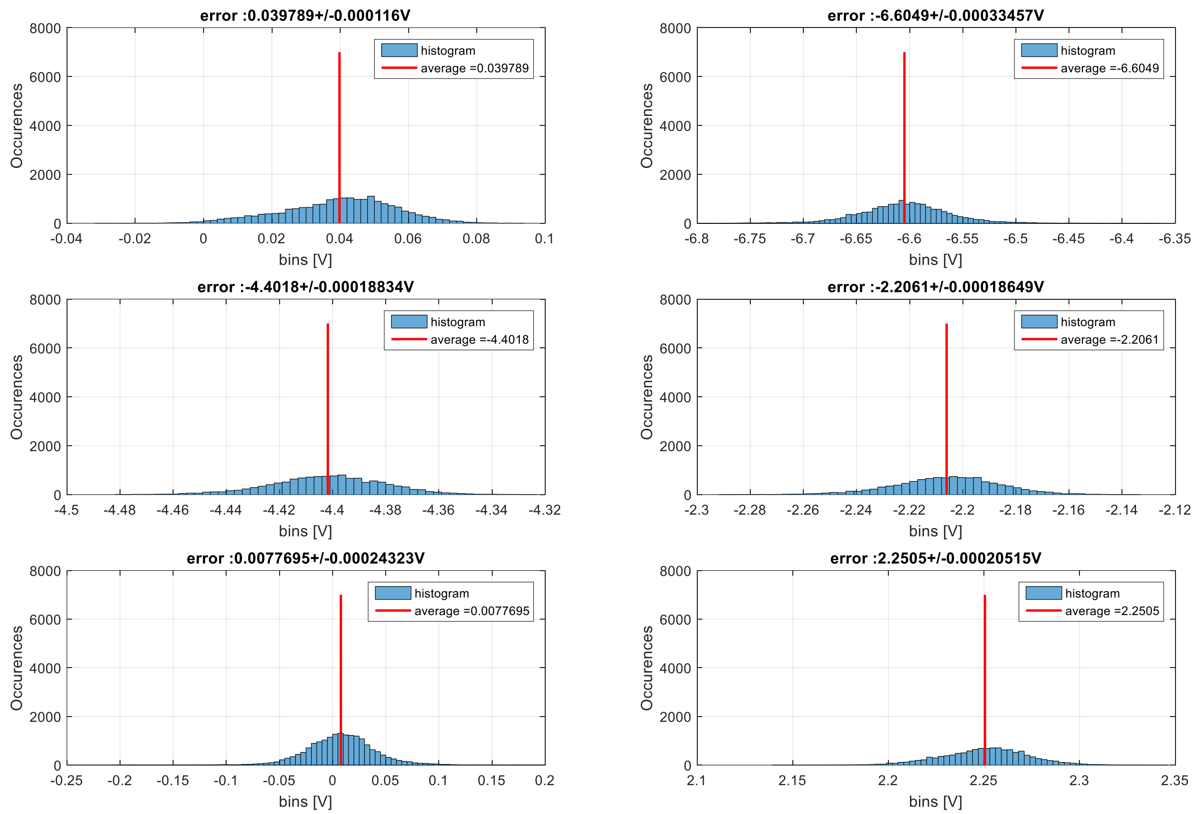

Figure 4: WP1 distribution for each elevation of the calibration

Table 3: Linear regression values

[nd]\[mm]	0	-300	-200	-100	0	100	intercept	slope
WP1	0.039789	-6.60492	-4.40179	-2.20608	0.007769	2.250465	0.025428991	0.022134691
WP2	0.025131	-6.53408	-4.3663	-2.20065	0.005854	2.259846	0.028057251	0.02195708
WP3	-0.02371	-6.49617	-4.32167	-2.16778	-0.03197	2.058112	-0.0455235	0.021420068
WP4	-0.01881	-7.07807	-4.92648	-2.59034	-0.06645	2.49958	-0.02804703	0.024024576
WP5	-0.00672	-6.89152	-4.68926	-2.39104	-0.07823	2.200492	-0.07109544	0.022859431
WP6	-0.09405	-7.2485	-4.91679	-2.70838	-0.28365	2.290077	-0.17741258	0.023793651
avg of avg	-0.01306	-6.80888	-4.60371	-2.37738	-0.07445	2.259762	-0.04476538	0.02269825

the next step in the methodology is quantify the uncertainty of a linear regression analysis and the transfer function to convert voltage to physical units. Whilst the ITTC procedures provide a number of linear regression analysis methods, it does not provide guidance on the interpretation of the results.

4.2. Comparison

When the calibration of all six waves probes was complete, a series of new tests were conducted with the voltage to elevation scaling applied in the data acquisition system. This scaling is express the minimum voltage for the minimum elevation and the maximum voltage for the maximum elevation in order to provide a linear correlation.

A comparison was conducted to calculate the voltage from the elevation recorded with the intercept and slope from the min/max values input in LabVIEW. From this voltage we calculate a new elevation using the intercept and slope from the linear regression equations to examine the impact.

Table 5: WPI results from ITTC procedure

Inv 2T student t @ 95% confident	2.570581836							
x values [mm]	0	-300	-200	-100	0	100		
x average [mm]	-83.33333333							
Sxx	150000							
Wave Probe 1								
y values [V]	0.039788576	-6.6049	-4.4018	-2.2061	0.00777	2.25046		
intercept [V]	0.025428991							
slope [V/mm]	0.022134691							
Residual	0.014359585	0.01006	-0.0003	-0.018	-0.0177	0.01157	Res = yi-a-bxi	
Res.^2	0.000206198	0.0001	8.1E-08	0.00033	0.00031	0.00013		
SSR	0.001078567	Sum of the square of residuals						
SEE	0.016420769	Standard error estimation						
Standardized residual	0.874477016	0.61257	-0.0173	-1.0986	-1.0754	0.70438		
ub	4.23982E-05	uncertainty in slope						
ua	0.006703751	uncertainty in intercept						
uncertainty for the curve fit (mm)	+|- 2.831099965	+|- 3.13	+|- 2.88	+|- 2.78	+|- 2.83	+|- 3.03	+|- 2.913630731	
A	-1.1488297	A = -a/b						
B	45.17795064	B = 1/b						
equation for conversion to physical unit	A+B*Voltage							
Inverse equation	(Phys.Unit-A)/B							

Table 4: Min/max value used in LabVIEW scaling

	min	max	intercept	slope
x	-300	100	intercept	slope
y WP1	-6.6	2.25	0.0375	0.022125
y WP2	-6.5	2.25	0.0625	0.021875
y WP3	-6.5	2.05	-0.0875	0.021375
y WP4	-7.078	2.49	0.098	0.02392
y WP5	-6.9	2.2	-0.075	0.02275
y WP6	-7.25	2.3	-0.0875	0.023875

Table 6a: Comparison analysis for elevation

Record elevation[mm]				
Mean WP1	6.26	-296.84	107.24	6.33
Mean WP2	5.50	-295.55	108.12	4.71
Mean WP3	10.41	-292.28	111.15	9.75
Mean WP4	0.32	-295.52	113.34	0.81
Mean WP5	11.27	-294.13	112.45	10.93
Mean WP6	4.63	-293.20	111.11	3.20

Table 6b: Comparison analysis voltage estimates

Estimation of Voltage (V)				
Mean WP1	0.176	-6.530	2.410	0.178
Mean WP2	0.183	-6.403	2.428	0.165
Mean WP3	0.135	-6.335	2.288	0.121
Mean WP4	0.106	-6.971	2.809	0.117
Mean WP5	0.181	-6.766	2.483	0.174
Mean WP6	0.023	-7.088	2.565	-0.011

Table 6c: Comparison analysis elevation estimates

Estimation of Voltage (V)				
Mean WP1	0.176	-6.530	2.410	0.178
Mean WP2	0.183	-6.403	2.428	0.165
Mean WP3	0.135	-6.335	2.288	0.121
Mean WP4	0.106	-6.971	2.809	0.117
Mean WP5	0.181	-6.766	2.483	0.174
Mean WP6	0.023	-7.088	2.565	-0.011

Table 6d: Comparison analysis elevation difference

	Elevation Difference [mm]				Mean
WP1	-0.543	-0.675	-0.498	-0.543	-0.565
WP2	-1.548	-2.673	-1.164	-1.551	-1.734
WP3	1.982	1.345	2.194	1.980	1.875
WP4	-5.245	-6.533	-4.753	-5.243	-5.444
WP5	0.225	-1.237	0.709	0.223	-0.020
WP6	-3.795	-2.776	-4.159	-3.790	-3.630

This method doesn't express a standard error but highlights the importance of taking a suitable fit to the voltage to elevation equation to minimise uncertainty in data acquisition.

According to the method in Measurements and their Uncertainties quoted earlier in this report. For each probe we can evaluate the standard error from the noisy signal when it's at a constant elevation level. This work was conducted for the voltage signal and also the elevation signal.

For the calculation we took the same ranges used to determine the mean values. The table with the different uncertainties are given below.

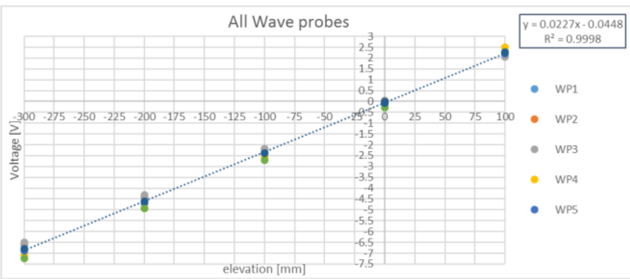

Figure 5: All wave probes signal from the calibration

5. DISCUSSION AND FURTHER WORK

The results from the linear regression are well correlated with the mean values of each signal. In future tests it could be beneficial to increase the averaging period at each wave probe elevation to allow the impact of oscillations on the water surface to reduce. The calculations outlined in the ITTC procedure require further development into standardised methodologies to allow interpretation of the associated uncertainty.

6. CONCLUSION

The linear regression analysis show that the wave probes have a correlation coefficient equal at more than 0.99. The noisy signal give standard error around +/- 0.2 mV but if we do the same calculation on the noisy signal in millimetres we got a standard error around +/-0.015 mm which doesn't represent the +/- 0.2 mV. More work is required on the record signal in millimetres to identify the relation between the two uncertainties.

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