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VERIFICATION OF MODIFIED KEOFLOAT SYSTEM TO MINIMISE WAVE HEIGHT INACCURACIES IN A 3D PHYSICAL MODEL RESULTING FROM ROTATION

JOHAN KIEVIET[1], MARIO AUGUST [2], CHRISTOPHE TROCH1[1]

1 CSIR, South Africa, jkieviet@csir.co.za, maugust@csir.co.za, ctroch@csir.co.za

ABSTRACT

A modification to the Keofloat system has been developed to address the effect that rotation about its vertical axes may have on the quantities effecting measurement accuracy of the system. The effect of rotation was not previously determined and was found to rarely occur in specific locations for some three-dimensional models. Consequently, the Keofloat design was modified from having a single suspension string to a double suspension string supporting it. A single and double suspension string Keofloat was tested in a wave flume to compare the modified Keofloat to what was previously used. Tests were conducted for regular waves between 0.5 mm and 23 mm and wave periods of 0.8 s and 1.6 s. The testing conducted, included two sets of tests, one for direct comparison where rotation was not present and the other where controlled and nonintrusive rotation was generated on the single suspension string Keofloat. The tests show that the double suspension string Keofloat compared extremely good to the single suspension string Keofloat and can reliably be used to measure small waves in a harbour basin where factors causing rotation of the Keofloat might be present.

KEYWORDS: Keofloat, Wave steepness, Capacitance Gauge.

1 INTRODUCTION

Small-scale physical model studies are often used to quantify the wave agitation and moored ship motions inside a harbour. This usually requires the entire harbour basin or a large portion thereof to be modelled. This typically results in scales of 1:80 to 1:100 in order to fit the minimum required model area in the wave basin. The small scales coupled with wave attenuation inside a port, also leads to higher relative accuracy requirements with waves often being smaller than 10 mm inside the port.

It has been concluded from previous testing that the Keofloat corresponds well with capacitance gauges when measuring wave heights between 5 mm and 20 mm and is accurate to 0.2 mm. When compared to capacitance gauges for wave heights less than 5 mm, the Keofloat system gives better results with less noise (Terblanche *et al*., 2009).

It was however found that on rare occasions when the Keofloat is used, the Keofloat slowly rotates around its vertical axes as it moves up and down. Any symmetrical inconsistencies on the float might then lead to an additional frequency superimposed on the measurements. The height of which will be equal to the vertical inconsistency and the period equal to rate of rotation. Consequently, the Keofloat design was modified from having a single suspension string to a double suspension string supporting it.

Two different sets of tests have been conducted to compare measurements of a single suspension string Keofloat to that using a double suspension string. The first set was for direct comparison when the variable of rotation to the single suspension string Keofloat was eliminated. This was achieved by doing testing in a wave flume with a two-dimensional (2D) setup. The second was to generate rotation on the single suspension string Keofloat and compare the measurements with an adjacent double suspension string Keofloat which was not rotating. The second set of tests were also done in a wave flume where rotation was generated on the Keofloat using a single suspension string. The rotation was however controlled and nonintrusive. The generated rotation was similar to what has been observed on rare occasions in some three-dimensional (3D) models.

In both sets of tests, capacitance gauges have been used as a reference to verify the accuracy when incorporating the modification into the Keofloat system. A description of the system and model setup along with an analysis of the results is presented in this paper.

2 INTRODUCTION

In Terblanche *et al*. (2009), the Keofloat is originally described as a small white cylindrical polystyrene block with a distinct black horizontal band in the centre of the float. It is supported by a thin vertical nylon string. A video camera is then used to track the interface on the float. Sampling lines are selected on the video image so that the interface can be followed in time. A reference strip fixed in view of the camera is also tracked in time on the same video camera. The reference strip, also with distinct black and white interface bands is used to convert displacement in pixels to displacement in millimetres.

Natural light entering the laboratory throughout the day can however results in light intensity changes during testing. For this reason, the black bands as described in Terblanche *et al*. (2009), has been replaced by white reflective bands on a matt black background. In addition, a light has also been added to the system and is positioned near the lens facing the Keofloat and reference strip. This increases visibility of the white reflective bands on the Keofloat and reference strip. It also ensures consistent light intensity when tracking the interfaces in time. The video camera and light is fixed in position to obtain optimal zoom. The camera setup as well as Keofloats and reference strip is shown in Figure 1.

Figure 1. Camera and light setup (left), Keofloats and reference strip (right).

For tracking of the interface between the mat black and white reflective lines, the exposure is lowered and video output set to black and white. The sampling lines is then positioned over the portions which is tracked for the Keofloats and the reference line. The positioning of these sampling lines is shown in Figure 2.

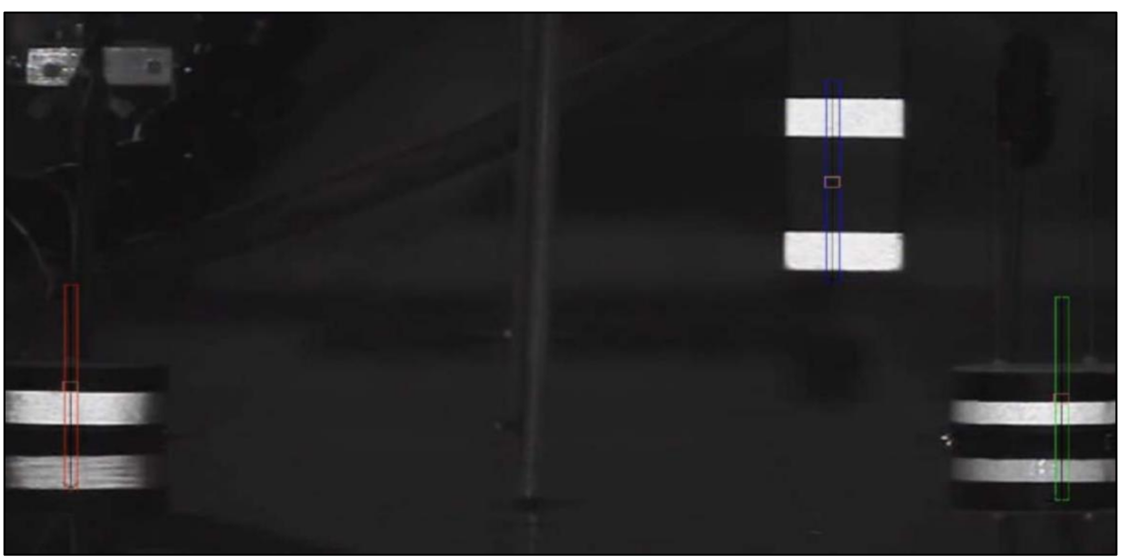

Figure 2. Positioning of sampling lines on Keofloats and reference strip.

The black over white interface sampling is along the vertical sampling lines, each with a width of about 6 mm. The actual pixel width of these sampling lines is about 20 pixels for the current setup. The pixel intensities is then averaged over the width of each sampling line and tracked in time. The tracked pixel columns are extracted from the camera image at a rate of 50 Hz and placed underneath each other into a merged image called a “keogram”. A keogram showing the results of the extracted video data is shown in Figure 3. The two undulated white bands correspond to the position of the two Keofloats while the two straight white bands correspond to the position of the reference strip. During the analysis of the Keogram in converting pixel displacements to millimetre displacements, Gaussian smoothing is applied to the average black/white interface to enhance the final resolution to about 1/10 of a pixel.

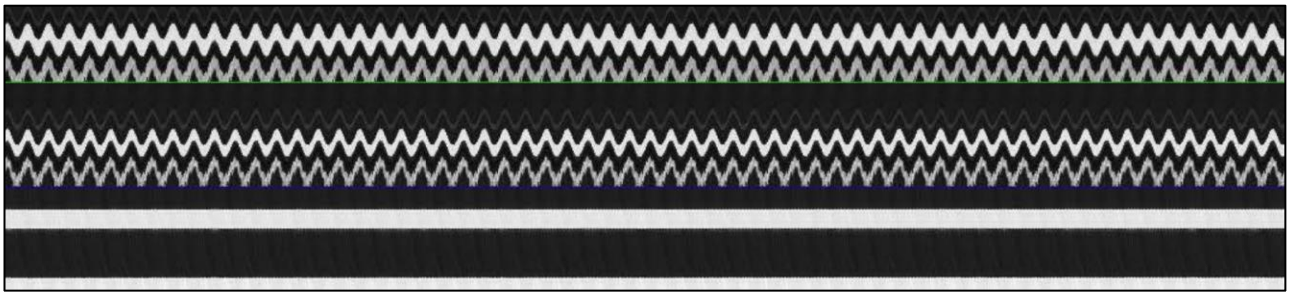

Figure 3. Keogram of two Keofloats and a reference strip.

Both Keofloats, using a single suspension string for support it as well as the double suspension string has a diameter, D = 40 mm and a height, H = 25 mm. For a wave amplitude a = 5 mm, wave period T = 0.8 s and a water depth of 346 mm the wave number k = 6.4 rad/m and wave steepness ka = 0.032. These values allow for the quantities effecting the accuracy of the measurement to be calculated. This wave condition when considering a typical model scale of 1:100, results in a typical, but rather high and steep wave in a model harbour basin.

The physical characteristics of the Keofloat as well as the mechanical characteristics of a typical wave condition is similar to what is used in Terblanche *et al*. (2009). The wave steepness to what was calculated is however slightly less, with it being 0.003 rad lower. This is due to the water depth being deeper for the current model setup. This results in a minute drop on the inaccuracies. It can therefore be assumed that utilising the values as presented in Terblanche *et al*. (2009), would be more conservative. The values as taken from Terblanche *et al*. (2009), are presented in Table 1 in summary form, and are applicable to the pre described wave condition.

Table 1. Quantities affecting accuracy of Keofloat measurements Terblanche *et al*. (2009).

Effect	Brief Description	Wave height error [mm]
Roll and pitch motions	Roll and pitch motions due to water level gradients	0.10
Hydrodynamics of the float	Effects of curvature of the wave crest and hydrodynamic mass and damping	0.02
Friction effects	Friction effects between the string and the float	0.01
Video monitoring system	Video monitoring system	0.10
Total accuracy of measured wave height	The hydrodynamic and friction effects positively counteract the effect of the pitch motions	≈ 0.20

3 MODEL SETUP

A shallow water wave generator was used to generate regular waves in a glass panel wave flume at the CSIR hydraulic laboratory in Stellenbosch. The wave flume has the following dimensions; 32 m long, 0.75 m wide and 1 m deep. An existing bathymetry was already constructed in the flume and was utilised for the Keofloat modification testing. This had a 3 m long 1:15 transition slope, starting at the 7 m grid line in front of the wavemaker. A gentle 1:1000 slope then follows up to the end of the wave flume where 13 - 19 mm absorption rock is located. A schematic drawing showing the flume test setup is shown in Figure 4.

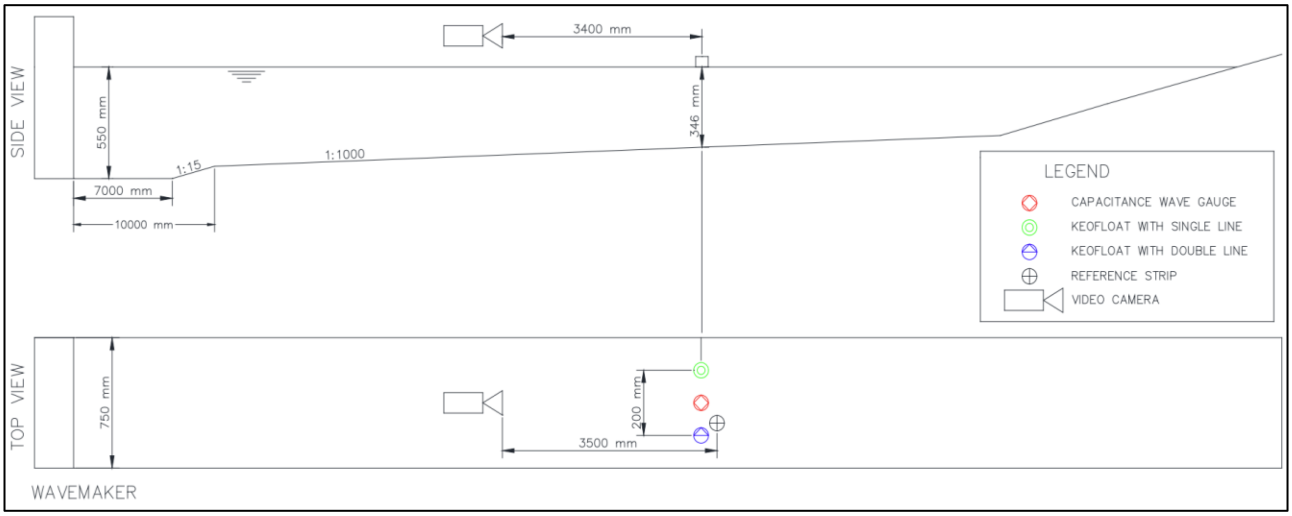

Figure 4. Schematic drawing of the flume test setup.

A capacitance gauge was installed on the centre line of the wave flume at a water depth of 346 mm. Keofloats were installed on both sides of the capacitance gauge, as shown in Figure 5, one with a single suspension string and the other with a double suspension string. This made it possible to obtain a direct comparison of the time series.

One video camera and one light was installed 3400 mm from the measurement location. The video camera is positioned to have the Keofloats and reference strip in view. The video image sequence of the camera is then sent to the computer for keogram analysis.

Figure 5. Photograph of the test setup showing the capacitance gauge and single and double string Keofloats.

4 COMPARISON IN REGULAR WAVES WITHOUT ROTATION

A series of tests were conducted with Keofloats with single and double suspension strings. A variety of regular wave conditions were generated to compare the performance of the double suspension string Keofloat to the single suspension string Keofloat. The conditions tested were for wave periods T = 0.8 s and T = 1.6 s with varying wave heights of H = 0.5 mm to H = 23 mm. For all conditions tested, wave absorption was enabled to allow for consistent regular waves being produced for each test.

Water elevations were recorded for a duration of 510 s. This included still water time before and after a test. The wavemaker started generating waves 30 s into a test and were stopped 440 s into a test. Waves were analysed for 145 s, starting 215 s into a test, and ending 360 s into a test. This presented in Figure 6, highlighting the section over which waves were analysed.

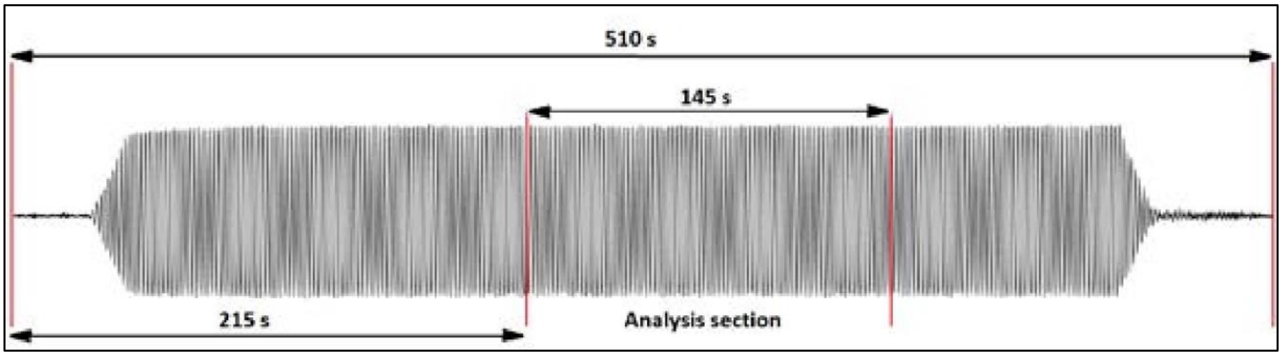

Figure 6. Analysis section for time domain analysis.

It can generally be seen from the time series for both the 0.8 s and 1.6 s wave period tests that the single and double suspension string Keofloats correspond well. For relatively small waves below *H* = 5 mm, the noise level for the capacitance gauge can visually be seen to be higher than that of the Keofloats, as shown in Figure 7, for *H* = 1.5 mm. Visual inspection of the time series for waves smaller than 20 mm reveals that flattened crests are measured by capacitance gauges. This flattening in crest values can be due to high frequency noise resulting in a "straight" line across the crest width after being electronically filtered out, as shown in Figure 7, for *H* = 10 mm as well as *H* = 15 mm. This flattening of crest values for the capacitance measurements is even more evident for the 1.6 s tests with longer wave crests. For waves between *H* = 15 mm and *H* = 23 mm tested, the capacitance gauges and Keofloats visually correspond very well, as shown in Figure 7, for *H* = 23 mm.

Abbreviations, "KF1", "KF2" and "CP" in the legend of all figures refer to "Keofloat with single suspension string", "Keofloat with double suspension string" and "Capacitance gauge" respectively. The time series presented in Figure 7, shows a slight phase lag between the capacitance and Keofloat measurements. This phase lag of less than 0.25 s is due to the two different acquisition systems being started manually at the same time. This however does not have an effect on the time series analysis.

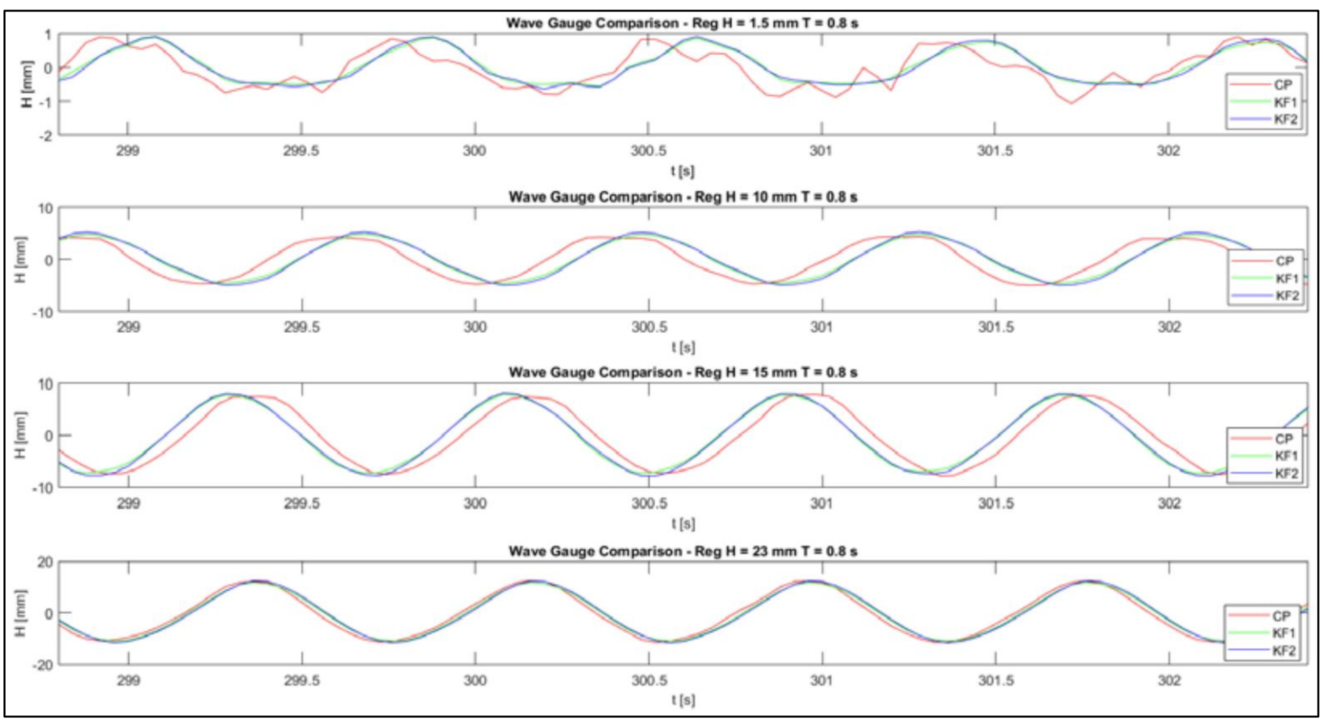

Figure 7. Time series measurements for 0.8 s regular waves.

A time series analysis has been done for all the tests. The various measurement gauges are compared based on the mean wave height and the standard deviation of the measured wave heights. The results for this are summarised in Table 2.

Table 2. Average wave period (T_z), Mean wave height (H_{mean}) and Standard deviation (σ_H) of measured wave heights for regular waves with input wave period T = 0.8 s and T = 1.6s.

Keofloat [1 string]			Keofloat [2 string]			Capacitance		
T_z [s]	H_{mean} [mm]	σ_H [mm]	T_z [s]	H_{mean} [mm]	σ_H [mm]	T_z [s]	H_{mean} [mm]	σ_H [mm]
0.8	0.53	0.10	0.8	0.57	0.03	0.3	0.52	0.24
0.8	1.34	0.09	0.8	1.48	0.08	0.7	1.14	0.42
0.8	4.25	0.13	0.8	5.18	0.14	0.8	4.79	0.26
0.8	5.63	0.04	0.8	6.47	0.05	0.8	5.69	0.24
0.8	9.44	0.05	0.8	10.25	0.04	0.8	9.18	0.24
0.8	12.26	0.06	0.8	12.66	0.04	0.8	12.04	0.24
0.8	14.96	0.16	0.8	15.74	0.16	0.8	15.14	0.30
0.8	17.38	0.12	0.8	18.50	0.10	0.8	17.85	0.28
0.8	20.23	0.04	0.8	21.19	0.03	0.8	20.86	0.26
0.8	22.78	0.09	0.8	23.95	0.07	0.8	23.49	0.27
1.3	0.74	0.22	1.0	0.58	0.34	0.5	0.65	0.32
1.3	1.78	0.75	1.3	1.72	0.61	1.2	1.91	0.77
1.6	4.80	0.05	1.6	4.79	0.04	1.6	4.51	0.22
1.6	7.32	0.04	1.6	7.29	0.04	1.6	6.60	0.20
1.6	10.23	0.18	1.6	10.26	0.17	1.6	9.32	0.18
1.6	13.08	0.16	1.6	13.05	0.11	1.6	11.86	0.22
1.6	15.37	0.16	1.6	15.50	0.14	1.6	14.31	0.25
1.6	17.79	0.20	1.6	17.83	0.19	1.6	16.98	0.23
1.6	20.86	0.12	1.6	20.77	0.10	1.6	19.47	0.20
1.6	22.56	0.09	1.6	22.78	0.08	1.6	21.89	0.19

When considering the 0.8 s wave period tests, the average wave height and period computed for waves smaller than 2 mm, shows a significantly higher standard wave height deviation for the capacitance measurements than for that of the Keofloats. The calculated average wave height and average wave period is also lower. This compares well to the results presented in Terblanche *et al*. (2009), and the statement that this is due to the higher noise on the capacitance gauge that is seen as small waves around the still water level.

For the 1.6 s wave period tests, both the Keofloats and capacitance gauge for waves smaller than 2 mm, shows a significantly higher standard deviation than for the rest the 1.6 s wave period tests. The high standard deviation together with the lower calculated average wave periods, indicate that this is due to higher noise ratios for relatively long period waves smaller than 2 mm. The results presented in Terblanche *et al*. (2009), does unfortunately not cover waves smaller than 2 mm for 1.6 s period waves and can therefore not be used for comparison to what has been measured for these wave conditions in the current study.

The standard deviation of the Keofloats is however still lower than that of the capacitance gauge for waves smaller than 2 mm. The lower standard deviation in wave height together with the more accurate calculated wave period indicate that although both systems have noise at these wave heights and relatively long wave period, the Keofloat is superior.

Wave height versus standard deviation plots presented in Figure 8 and Figure 9 for both the 0.8 s and 1.6 s wave period test shows a good correlation between the single and double suspension string Keofloat. Figure 8, highlight increased standard deviation values for wave heights around 6 mm and 15 mm for the 0.8 s wave period tests. Figure 9 similarly shows this being around 10 mm and 18 mm for the 1.6 s wave period tests. A similar trend of higher standard deviations around these wave heights is also present in the capacitance measurements.

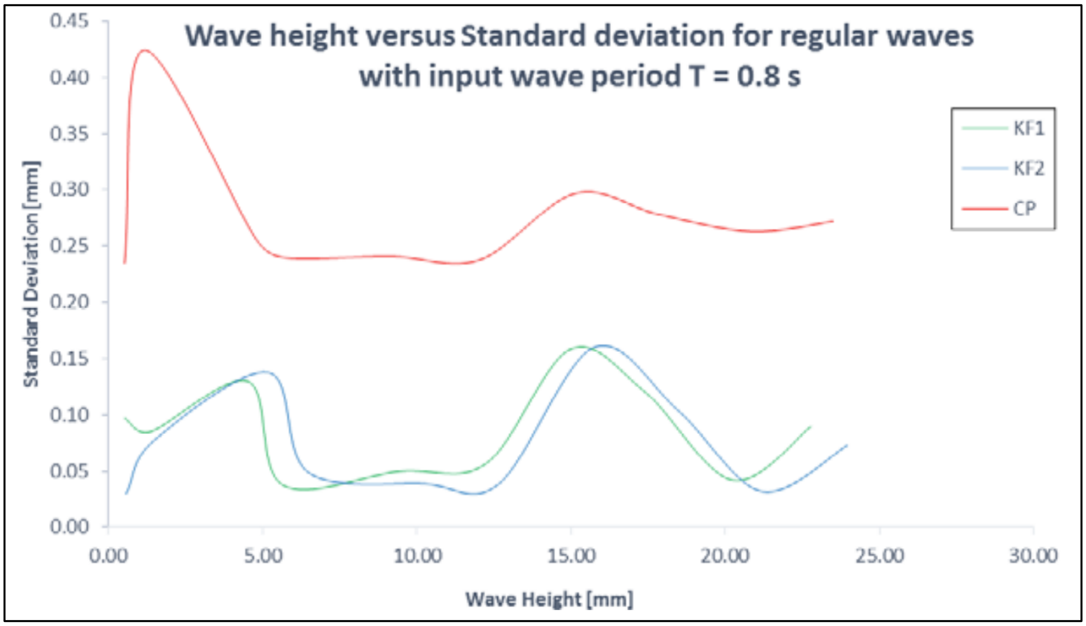

Figure 8. Wave height versus standard deviation for regular waves with input wave period T = 0.8 s.

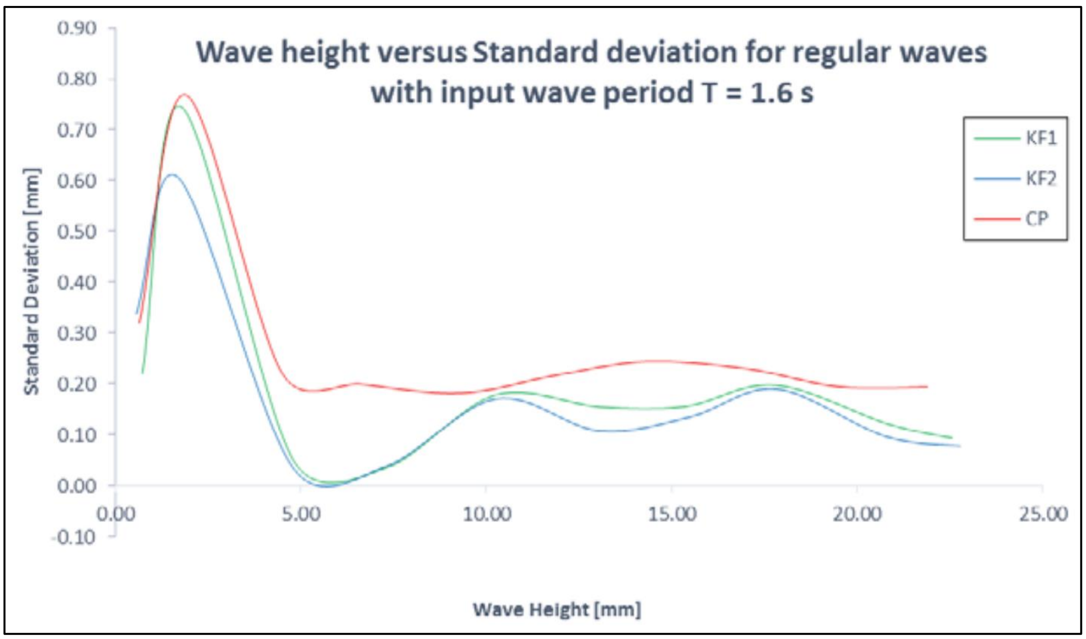

Figure 9. Wave height versus standard deviation for regular waves with input wave period T = 1.6 s.

In general Table 2 shows good correlation between the Keofloat and the capacitance system and compares well to the results presented in Terblanche *et al*. (2009). Figure 8 and Figure 9 shows good correlation between the single and double suspension string Keofloat.

5 COMPARISON IN REGULAR WAVES WITH ROTATION

A series of tests were conducted with Keofloats with single and double suspension strings. Except for the system used to create rotation on the single suspension string Keofloat, the test setup and analysis procedure is the same as what is used in Section 4. This series of tests includes two repeatability tests at still water and two repeatability tests with regular waves having a wave height H = 9 mm and T = 1.6 s. For all four tests the single suspension string Keofloat rotated at a controlled rate to quantify the effect that any symmetrical inconsistencies on the float might have on wave measurements. Controlled rotation was generated with the aid of a tweakable air hose. The air hose was positioned to gently blow air across the top edge of the Keofloat, as shown in Figure 10.

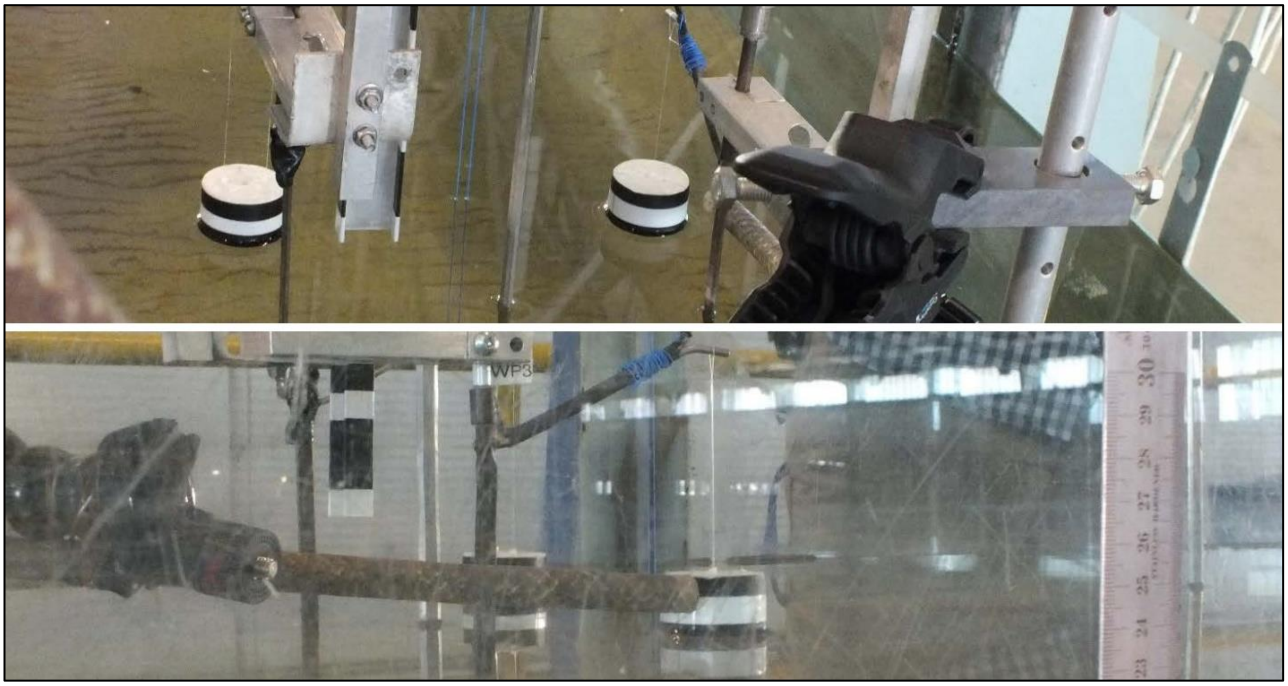

Figure 10. Wave height versus standard deviation for regular waves with input wave period T = 1.6 s.

As for the previous tests, a time series analysis has been done for the still water and the repeatability tests. The various measurement gauges are compared based on the mean wave height and the standard deviation of the measured wave heights. The results for this are summarised in Table 3. It can be seen from Table 3, that the repeatability of the still water and 9 mm wave height tests can be seen as consistent with the capacitance gauge and single suspension string Keofloat generally having the largest standard deviation of wave heights.

Table 3. Average wave period (T_z), Mean wave height (H_{mean}) and Standard deviation (σ_H) of measured wave heights for rotation tests at still water and H = 9 mm and T = 1.6 s.

Keofloat [1 string]			Keofloat [2 string]			Capacitance		
T_z [s]	H_{mean} [mm]	σ_H [mm]	T_z [s]	H_{mean} [mm]	σ_H [mm]	T_z [s]	H_{mean} [mm]	σ_H [mm]
Still	0.31	0.17	Still	0.07	0.04	Still	0.45	0.19
Still	0.30	0.16	Still	0.11	0.06	Still	0.46	0.20
1.6	7.30	0.21	1.6	7.18	0.12	1.6	6.74	0.21
1.6	7.30	0.47	1.6	7.02	0.39	1.6	6.72	0.18

The time series of the still water tests is presented in Figure 11. This shows the noise on the capacitance to be significantly higher than that for the Keofloats. The single suspension string Keofloat shows a measurement with amplitude $a \approx 0.3$ mm and $T \approx 3$s. The error due to rotation at still water can be approximated to be twice the amplitude of this measurement, which is roughly 0.6 mm. This can however be different for other Keofloats.

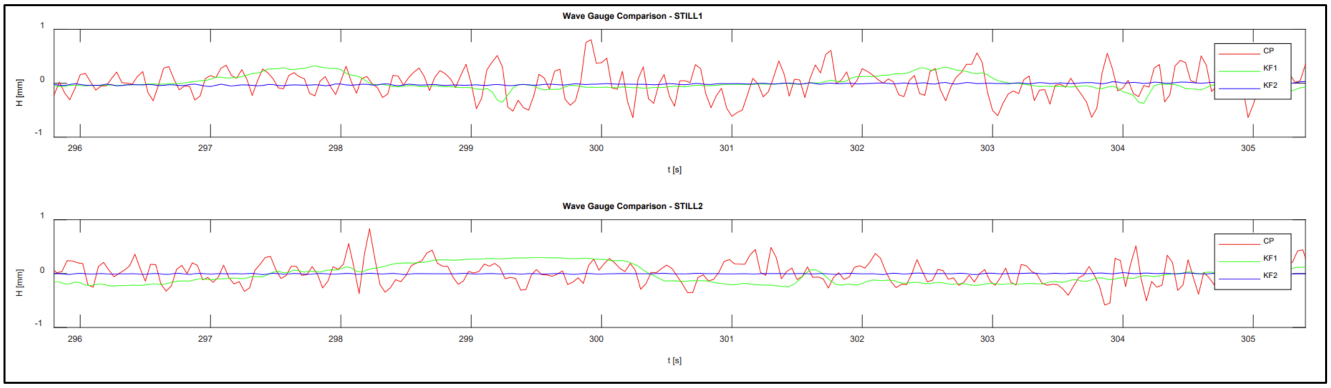

Figure 11. Time series measurements at still water with rotation on the single suspension string Keofloat.

The time series of a rotation test with regular waves is presented in Figure 12. For clarity, only the measurement data pertaining the two Keofloats have been included in the plot. To quantify the trend in peak differences seen in "KF1", the Keofloat data measurements have been put through a standard low pass filter with cut off frequency equal to twice the generated period (i.e. 3 s). These filtered data sets are also presented in Figure 12, on the same plot with abbreviations, "$KF1_{hf}$" and "$KF2_{hf}$" in the legend referring to the measured data put through the low pass filter.

As for the still water test, this shows a measurement error on the data set of the single suspension string Keofloat. This is a low frequency noise error with amplitude $a \approx 0.3$ mm and $T \approx 3$s. This is seen to be the same as for the still water test and is approximated at 0.6 mm.

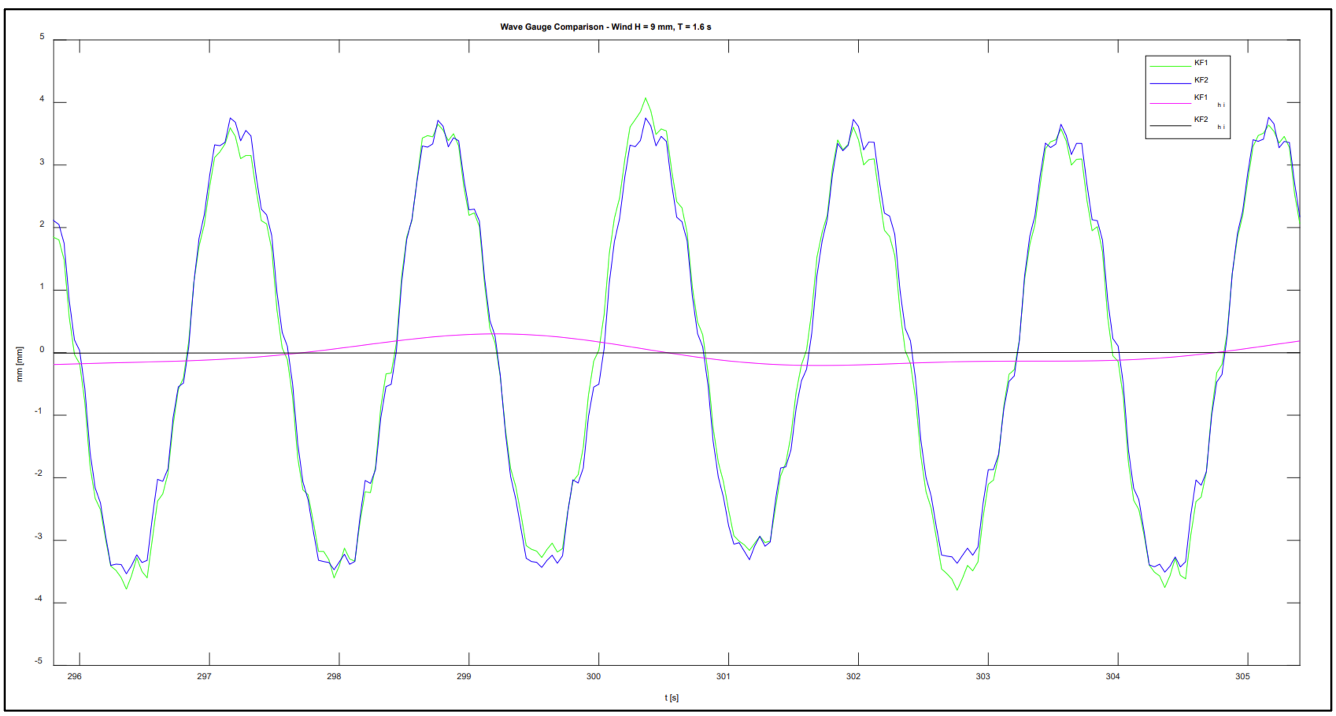

Figure 12. Time series measurements for regular waves with rotation on the single suspension string Keofloat.

6 CONCLUSIONS

Wave measurements have been conducted in a wave flume with relatively large, intermediate, and small wave heights to investigate the comparative performance of the two Keofloats, one with a single suspension string and the other a double suspension string. As with previous Keofloat research, a capacitance gauge was also used as a reference during all tests. Visual observations as well as time series comparisons between the single and double suspension string Keofloat, show good agreement and in general had similar standard deviations.

The trend of higher standard deviations around some wave heights during these tests were present on both the Keofloat and capacitance data acquisition systems. The two systems are uniquely different to each other, resulting in the only possible cause to be an external physical element which is present on the waves. Although unclear, it might be caused by the wave absorption system which creates this irregularity on the regular waves being generated.

A series of tests with generated rotation on the single suspension string Keofloat has also been conducted to investigate any effect which such rotation might have on the wave measurement. The rotation generated was similar to what has been observed in some 3D models. It has been concluded from the testing that the error due to rotation is approximately 0.6 mm.

From all visual observations and comparisons, it is concluded that the double suspension string Keofloat can reliably be used to measure small waves in a harbour basin where factors causing rotation of the Keofloat might be present.

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REFERENCES

Terblanche, L., Van der Molen, W., Moes, H., Hough, G. and Chemaly, M. (2009). Measurement of waves in a small-scale harbour basin using video monitoring technology. *Proc. Coasts & Ports 2009*. Wellington, New Zealand.