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Digital Sailmate: Enhancing Safety through Low-Cost Stability Monitoring in Artisanal Fishing

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ABSTRACT

Despite overall mortality decreasing, offshore fishing remains one of the riskiest work-based activities worldwide. For example, fishing communities in East Africa have a 43-fold higher rate of drowning than the general population. A lack of safety culture and knowledge around vessel stability contributes to this issue. Formal safety measures can be difficult to enforce, especially in small scale and subsistence fishing activities dominated by small artisanal boats. Digital technologies hold potential to effectively improve fishing safety. A digital safety device based on commonly held and relatively low-cost consumer products such as smartphones can provide increasing information to fishers enabling more informed safety decisions to be taken during vessel use. This paper proposes the algorithms for a prototype device to monitor stability of fishing vessels, with focus on the capabilities of low-fidelity data in stability assessment. The findings of experimental results at model and full scale are presented. The research indicates that an inclining test can be carried out with minimal training or knowledge base to allow an adequate stability assessment of a vessel before departure on a fishing trip. This baseline measure can then be used to track stability whilst underway as vessel motion is recorded and processed continually updating the stability assessment.

KEY WORDS

Safety; Fishing vessels; Digital Technology; Stability; Accessibility.

INTRODUCTION

Globally, offshore fishing remains one of the most dangerous occupations (Jensen et al., 2014; Roberts et al., 2021; Womack, 2003) and is especially hazardous for artisanal fishers in low- and middle-income countries (LMICs). Willis et al. (2023) estimate the global mortality rate at over 100,000 fishers a year. Insufficient vessel stability, leading to capsize, is a key aspect of this safety crisis. This research proposes that providing more information about the stability condition of a vessel enables fishers to make more informed decisions on operational safety. This information can be collected, analysed, and then communicated to fishers via a low-cost digital device that measures and monitors vessel stability.

The paper links the problem of fishing boat safety due to loss in stability to the opportunity that low-cost consumer level digital technology provides. The premise of this research is that low fidelity data may be used for stability assessment in a low-cost system. The focus of the paper is the initial testing of a prototype device with the ability to both measure stability in a controlled procedure and monitor vessel stability during normal operations.

The case study for this project investigates artisanal fishing vessels in East Africa. Tests are carried out in two environments, model scale testing in laboratory wave tanks and a full-scale pilot study on a fishing boat in a harbour. The model scale tests demonstrate some of the difficulties in applying a sensor to measure the underlying natural roll period of a vessel in a discrete frequency wave train such as is generated in a smaller wave tank. The full-scale study demonstrates improved results from real wave environments and suggests the applicability of the approach to develop a full featured safety application.

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BACKGROUND

Fishing Boat Safety

In high-income countries (HICs) mortality rates of fishers are over 100 per 100,000 fisher-years (Sindall et al., 2022). Mortality rates in low- and middle-income countries (LMICs) are not as well documented and are estimated to range from 2 to 5 times more than the mortality in HICs (Sindall et al., 2022). Regardless of the economic development of the country, in both LMICs and HICs most deaths are associated with capsizing of boats, due to bad weather conditions or economic pressures resulting in fishers overloading vessels or going out in conditions unsuitable for their vessels (Sindall et al., 2022).

This study focuses on Kenya as a case study location. The fishing industry in Kenya employs over 60,000 fishers directly and 1.2 million indirectly through fishing, production, and supply chains. The areas of fish production in Kenya are the coast and open sea, freshwater lakes, such as Lake Victoria, rivers, and man-made dams. Across the country, use of traditional canoes, small dhows (*mashua*) and outriggers dominates, with less than 10% of these being motorised (Kimani et al., 2018). Examples of these vessels can be seen in Figure 1.

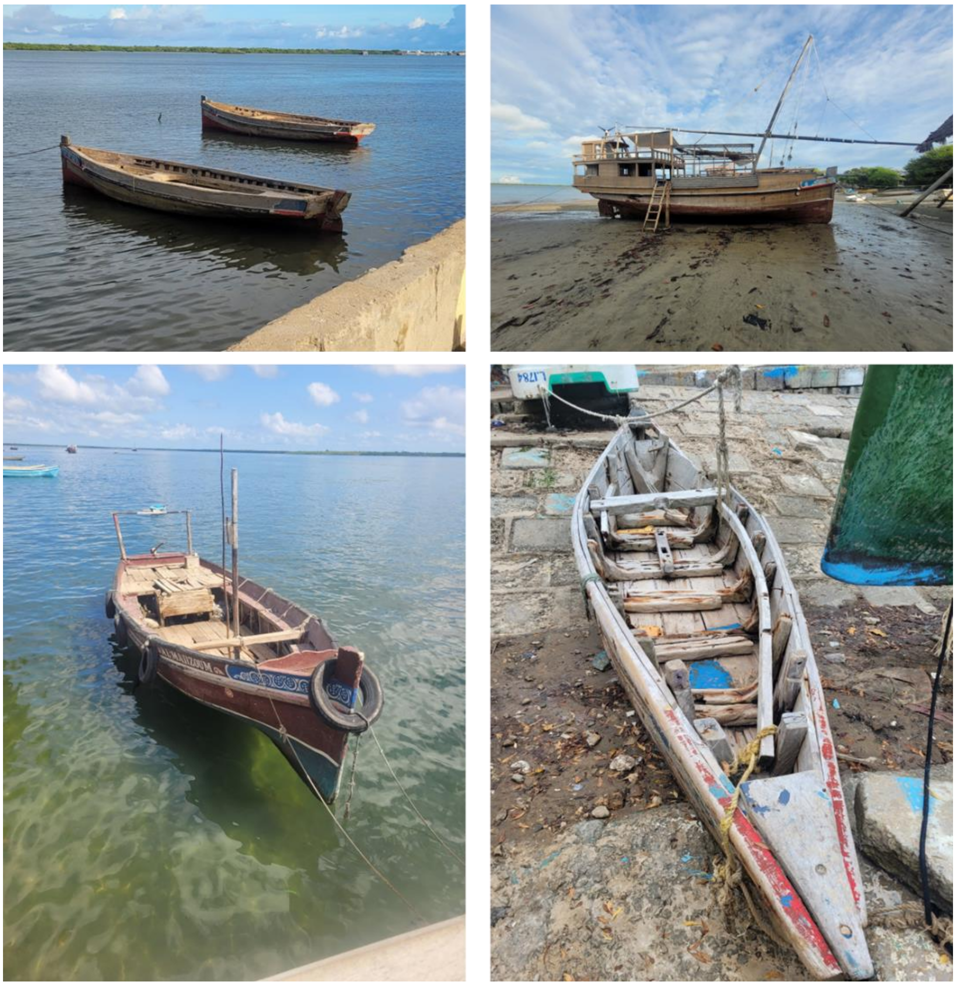

Figure 1: Typical Artisanal Vessels. Mid-size dhows (top left, bottom left), large sailing dhow (top right), small canoe (bottom right)

There is a lack of data on drowning fatalities in East Africa, especially among coastal communities with many studies based around Lake Victoria. There have been several studies into the epidemiology of drowning around Lake Victoria, using techniques such as verbal autopsies (Opemo et al., 2014). Such techniques can be difficult to scale up from communities to a regional level and there remains a lack of official figures. Fishing communities in East Africa were found to be at a higher risk of drowning with a 43-fold higher incidence of drowning than in the general population (Whitworth et al., 2019), which was mostly associated to the lack of safety equipment such as life jackets (97% of cases) and the inability to swim. Many of these cases were likely initiated by a capsizing or other stability driven event.

The annual estimated number of deaths on Lake Victoria has been reducing from between 3000 and 5000 in 2014 (International Federation of Red Cross and Red Crescent Societies, 2014) to around 1500 in 2020 (Watkiss et al., 2020).

The reduction was mostly attributed to greater use of life jackets and a trend for larger boats. Although it is not known how many boats capsize due to loss of stability, around two thirds of drowning deaths a year can be attributed to the weather conditions (Watkiss et al., 2020).

Stability Challenges

The risks within fishing which can lead to drowning include combinations of human and physical factors. One fundamental risk is that the boat is compromised during fishing operations through capsize or damage, thereby putting the crew at risk of entering the water. Stability can change quickly during onboarding of a catch bringing extra weight into the boat and moving the centre of gravity upwards. Associated risks around swimming ability and the lack of personal flotation devices means that capsize is a significant risk factor for drowning. Measures to improve the stability characteristics of fishing vessels can therefore reduce drowning risks.

Stability related accidents have the most causalities as they often happen suddenly meaning crew cannot access safety devices such as lifejackets. For this reason, it is important that vessels have their stability conditions assessed before coming up against potentially dangerous conditions. Vessels under 24 metres have a much higher rate of accidents caused by stability conditions than larger vessels which are generally better equipped to deal with adverse conditions due to the size of the vessel and crew training. Although crews of small and medium vessels can assess the stability of the vessel, this is in most cases based off previous experience and it may be difficult to assess a reduction in stability (Míguez González et al., 2012).

The most common issues on fishing vessels that lead to stability problems are changes in weight distribution, operational situations, weather situations and dynamic instabilities (Míguez González et al., 2012).

- **Changes in weight distribution** leading to change of location of centre of gravity. This can be from changes in structure, equipment or the use of spaces that are not tracked and recalculated leading to potentially dangerous loading conditions. This may include changes in ballasting and any modifications made to vessels.
- **Operational situations** such as inappropriate or overloading the vessel, raising the centre of gravity. Additionally suspended loads or fishing gear may change stability conditions particularly in the case of nets grounding the will cause loss of stern freeboard.
- **Weather situations** such as water intake in heavy rains – especially relevant on small open vessels. Breaking waves are particularly dangerous in beam seas, and high winds will create greater heel angles which in both cases vessels with a reduced stability condition will be more susceptible to capsize.
- **Dynamic instabilities** related to the interaction of the vessel underway and waves such as parametric resonance where the vessel will experience high amplitude rolling motions, losses of stability or steering capacity due to sailing in following seas or quartering seas.

Digital Safety Devices

Digital devices with safety features for personal use are becoming increasingly prevalent, such as sensors in smartwatches able to contact emergency services after a fall is detected. Decreasing cost and increasing sophistication has allowed development of technologies integrating into workplaces and everyday life. Access to technology such as smartphones is now prevalent in LMICs and presents opportunities to develop safety features useful for hazardous activities such as fishing.

Access to mobile phones is increasing in Kenya, with 94.6% of the population owning or having access to a SIM card, (Van Hove & Dubus, 2019). The use of smartphones is lower, with 33.9% of the phone owning population having smartphones and 52.8% owning basic phones (text and call features only) (Jelassi & Martínez-López, 2020; Krell et al., 2021; Van Hove & Dubus, 2019). This statistic is likely to increase rapidly as smartphone technology becomes further accepted, especially amongst younger people.

There are several existing technologies to estimate a boat's stability based on gyroscopic motion and baseline information about a vessel. The SKIPPER software gives updating stability condition with risk level for vessel and the maximum recommended wave height. To use the software information about the hull form, tanks and holds, flooding points, decks, minimum freeboard, lightweight and other ship particulars need to be inputted (Míguez González et al., 2012). This makes the makes it effective on industrialised vessels where a stability matrix as seen in Womack (2003) would become too large and complex. Needing a large amount of data about the vessel makes the software more difficult to set up on traditional fishing boats where much of the data needed is unlikely to be known. Building from this paper, the Kora Kora mobile application uses a similar concept focusing on Indonesian fishing vessels (Grech La Rosa et al., 2022). This uses an app to measure roll period to collect data which can be used to provide a measure of vessel stability which is then presented in a traffic light system.

Another study proposed a device to monitor draft and stability from a vessel rolling motion, this found the current waterline of the vessel through the roll motion then made use of the displacement-draught curve to find total displacement. When a given limit is reached the device detects this and alert the crew (Sakib, 2015). This method requires a displacement -draught curve for the vessel which is not a realistic prerequisite for artisanal vessels in LMICs. The existence of these technologies show the potential for linking the issue of fishing boat safety due to the loss in stability with the opportunity presented by low-cost consumer level digital technology.

METHODOLOGY

Approach

The core principle of this research is that a vessel's roll motion, measured by a gyroscope, can be directly linked to vessel stability through the estimation of the metacentric height. This link, which is an established naval architecture technique, is explained in the following subsections. The novelty within this research is to apply this technique using a low-cost consumer device such as a smartphone, single board microcontroller or computer, and without the direct intervention of a stability expert. The device will give fishers an insight into the stability condition of the vessel allowing them to visualise significant changes in stability and make more informed decisions during operations.

The device requires capability to monitor motions for three types of tests:

- Inclining Test: A well established and widely used method for finding vessel metacentric height (GM). Found by moving weights to create heel angles and recording the angle change.
- Roll Test: Commonly only used on smaller vessels such as fishing vessels. A heel angle is created, and the vessel then allowed to oscillate. Generally considered less accurate than the inclining test but can be more accessible in a practical environment.
- Continuous Monitoring: Using the same principles as the roll test, a device can continuously measure the roll period and provide an immediate estimate of a vessel's stability condition.

In this paper a device, detailed below, is tested at two scales and locations. Firstly, a series of model scale wave tank tests using a 1 metre length model of an artisanal fishing boat, and secondly a full-scale pilot test in a harbour using a 5 metre length open deck fishing boat. Further tests will be undertaken on typical artisanal fishing boats in Kenya but are not reported in this paper.

Stability Tests

Principles.

The metacentric height, GM, is a measure of static stability on a floating object. It defines the distance between the object's centre of gravity and the stability position known as the metacentre. When GM is greater than zero a boat is considered stable, meaning it will return to its upright equilibrium position. Maintaining sufficient positive GM, also to account for dynamic effects, is an important criterion for vessel safety. For larger ships GM is part of a regulated stability assessment which accounts for different loading conditions, damage, dynamic effects, and additional aspects such as wind loading. For smaller boats, especially in LMIC settings, assessing GM may not be a regulatory requirement, but it still provides a fundamental practical measure of stability and motion behaviour.

A larger GM gives more initial stability but also a shorter roll period (Biran, 2003), commonly known as being stiff. Conversely a lower GM causes the vessel to roll more slowly, known as being tender. For a vessel to be considered safe the GM needs to be positive with margins depending on boat type and operational area. The requirements for measuring GM depend on the boat type and the country it is operating in.

For example, the Maritime and Coastguard Agency in the United Kingdom issue guidance for fishing vessels under 15 metres registered length. The guidance advises exciting the vessel externally using a rope, once the vessel is rolling sufficiently the motion is allowed to decay and the average time of each oscillation is taken and is compared to the beam of the vessel to determine its safety (Maritime & Coastguard Agency, 2022).

Inclining test.

The inclining test is a well-established and widely used method to find GM for a vessel in its 'as built' condition and whilst in service. This is essential for ships to meet regulatory stability criteria. The test is conducted by moving known weights a given distance across the ship to create a small angle of heel. The angle of heel is found by recording the position of a pendulum or angle meter before and after the weight is moved. This can then be fed into an equation to find GM for small angles of heel. This method will be used to find GM using the inclining test feature of the device. The GM can then be used to validate results and compare accuracy during further testing.

Roll test.

The roll period stability test is performed by creating a heel angle on a vessel and allowing oscillation at the natural roll frequency. On small vessels this is done by the crew moving to one side of the vessel to induce the heel angle and then moving back to the centre line to allow the vessel to oscillate or by using a rope to induce a roll motion. From this the roll period is measured and GM can be estimated. This is generally a less accurate measure of GM than the inclining experiment due to the estimation of the roll radius of gyration. However, it is a more accessible method with simpler analysis required to produce a result. For this reason, it is often used for small vessels, particularly fishing vessels (Maritime and Coastguard Agency, 2009).

The Weiss formula (Weiß, 1953, as cited in Kobylinski & Kastner, 2003; Santiago Caamaño et al., 2022; Grech La Rosa et al., 2022) as shown in Equation 1 can be used to find the natural roll frequency, ω_0 :

$$\omega_0 = \frac{\sqrt{g * GM}}{k_{xx}} \quad [1]$$

Where k_{xx} = the total roll radius of gyration in meters [m], GM = metacentric height in meters [m] and g = acceleration due to gravity $\left[\frac{m}{s^2}\right]$.

As seen in Santiago Caamaño et al. (2019) and Grech La Rosa et al. (2022), the roll radius of gyration can be estimated as:

$$k_{xx} = 0.4 * B \quad [2]$$

Where $B =$ vessel beam in meters [m]. By rearranging for the metacentric height this method enables an immediate estimate of vessel stability in uncontrolled environmental conditions. Therefore, it can potentially be used to predict progressive changes in different settings, such as during operations where the vessel loading condition may change or weather-related instabilities. This technique will form the basis of the prototype algorithm.

Continuous monitoring.

The continuous monitoring function uses the same principles as the roll tests but requires a more elaborate data processing approach. As the vessel carries out normal operations the device monitors the roll motion of the vessel. As shown in this study, the estimation of natural roll period from a continuous signal is challenging. It requires an algorithm to find consistent peak frequencies through signal analysis such as Fast Fourier Transform (FFT). The tracking of these peak frequencies over time can then be used to detect significant changes that may occur due to a shift of the centre of gravity, for example in the case of loading a vessel with a catch of fish when out at sea. It is important to detect these changes quickly as when the vessel is suddenly put in adverse conditions the change in stability can rapidly lead to capsize.

Experimental Flow

Figure 2 describes the experimental flow of the prototype device for all three types of stability test (inclining test, roll test and continuous monitoring). The first step is to first ensure the vessel is loaded in its normal operating condition prior to testing. Then the appropriate measurements of the vessel are taken to estimate displacement. The prototype is securely fastened to the vessel on a flat surface with the gyroscope appropriately aligned to the centreline of the vessel. The vessel is allowed to settle before testing begins and ideally weather conditions should be calm. Baseline motion data is collected to allow the device to calibrate itself. One or more of the three tests is then performed. The output can then be immediately used, for example to provide an alert. It is also saved for later analysis.

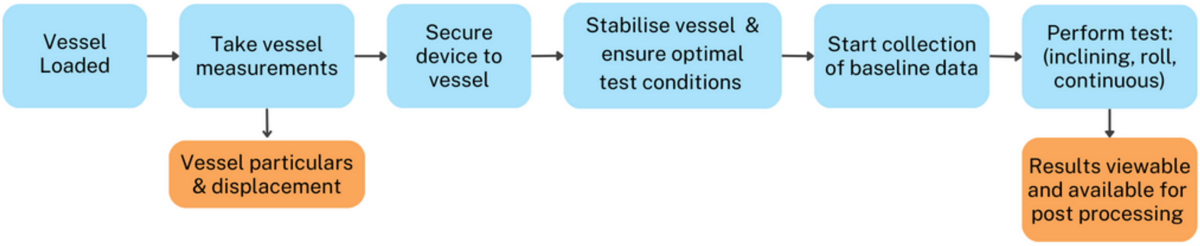

Figure 2: Experimental Flowchart

The Device

To measure roll motion on a vessel using a low-cost system operated by the fisher, a device with the following criteria is needed (Table 1):

Table 1: Device Requirements and Capabilities

Requirement Description	**Requirement value**	**Prototype Device Specification**
Measurements	Gyroscope to measure roll motion	MPU-6050 Accelerometer and Gyroscope
Cost	Low	Approx. £70 - £150, dependant on setup (addition of screen, fans etc.)
Power	< 10W	Variable, with a maximum draw of 6W
Sample rate	Adjustable, with capability of at least 100 Hz sample rate.	Sample rate set in algorithm. Capable of 1kHz sample rate.
Timescales	Storage capacity for several days of continuous measurement	32GB SD card capable of storing raw data for over 100 days of continuous running.
Size	Portable and small. Larger devices should have a carry case with handle.	157 x 82 x 41 mm in case without screen (no handle) 270 x 246 x 124 mm in case with screen (with handle)
Scale	Suitable for both model and full-scale measurements.	Yes
Environmental protection	Waterproof case	Hard, buoyant, waterproof case
Battery	Sufficient for 1 day operation on a single charge	2 x 5000mAh will power Pi for up to 19 hours

The ambition of the present study is to apply the experimental flow on a cross platform smartphone app. However, this adds layers of unnecessary complexity in the initial prototyping stages. Therefore the prototype device is based on a Raspberry Pi single board microcomputer. The advantages to choosing this device are that it is easily accessible, simple to use, robust and low cost. Additionally, it is capable of both collecting and processing large datasets on the same device. It comes set up with an operating system (OS) and graphical user interface (GUI) making the initial set up of the device simple.

The Raspberry Pi is coupled with an MPU-6050 accelerometer and gyroscope unit, a low-cost sensor capable of measuring angular acceleration and rotation around 6 axes. The MPU-6050 is a Micro-Electro-Mechanical Systems (MEMS) module, the angle data produced by the unit may be considered low fidelity data, similar to that produced by a mobile phone. The Raspberry Pi is fixed within a waterproof case with the gyroscope fixed to the Pi alongside a battery and a charging cable.

To complete the experimental flow, shown in Figure 2, data is collected from the device and converted into degrees, then is filtered to remove noise and extreme values. The clean data is then ready for Fast Fourier Transform (FFT) analysis of the signal. The Fourier transform converts a signal from the time domain to the frequency domain enabling detection of the underlying natural roll period of the vessel.

Model Tests

Initial testing of the device was applied on a model scale fishing boat. It was considered important to test on a model relevant to the case study in East Africa so that the algorithm can be better tuned to the characteristics for these hull shapes. Vessels in the case study are noticeably different in style to many HIC settings in terms of the hull form shape, the powering (sails, motors etc) and the type of fishing operations (trawling vs line fishing).

The model used was a 20th scale model of a proposed 21 metre traditional Kenyan fishing dhow designed by the Flipflopi project (Flipflopi Project, 2017). The model was 3D printed enabling a lower cost yet accurate representation for stability and motion experiments. The model has a waterline length of 1.064 metres and is ballasted using metal weights fixed to the hull and deck. The vessel particulars are shown below in Table 2.

Table 2: Model and full-scale particulars

Vessel Particular	Full-scale	Model-scale
Water Line Length [metres]	21.38	1.064
Beam [metres]	6.75	0.338
Draught Amidships [metres]	2.50	0.125
Volume of Displacement [$metres^3$]	17.66	0.017

The model has one full wooden deck and a second partial deck at midships to allow for a standardised vertical movement of weights to simulate multiple loading conditions across different tests. Figure 3 shows the 3 different loading conditions relative to each other:

- Low Position: Weight on vessel deck (baseline)
- Mid Position: Weight on top of foam blocks on vessel deck (decreasing value of GM by 2.4%)
- High Position: Weight on top of second deck (decreasing value of GM by 20%)

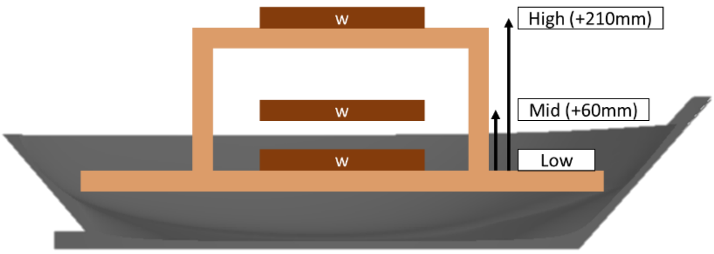

Figure 3: Model weight positions: Low (baseline), Mid (+60mm), High (+210mm)

For each inclining test, it was ensured that the model was in the correct loading condition and all weights were securely fixed. The inclining weights were placed on the deck with the prototype device and an inclinometer. To validate results from the prototype device the inclining tests were initially run both through the prototype and manually using the inclinometer.

Model testing was carried out at Newcastle University across the Wind Wave Current Tank (WWCT) and the Towing Tank (TT) shown in Figure 4, which have the dimensions shown in Table 3:

Table 3: Testing facilities main parameters.

Parameter	Towing Tank	Wind Wave Current Tank
Length [metres]	37	11
Width [metres]	3.7	1.8
Water Depth [metres]	1.25	1.0
Wave Period [seconds]	0.5-2.0	0.8-4.0
Wave Height [metres] (period dependant)	0.02-0.12	0.02-0.2

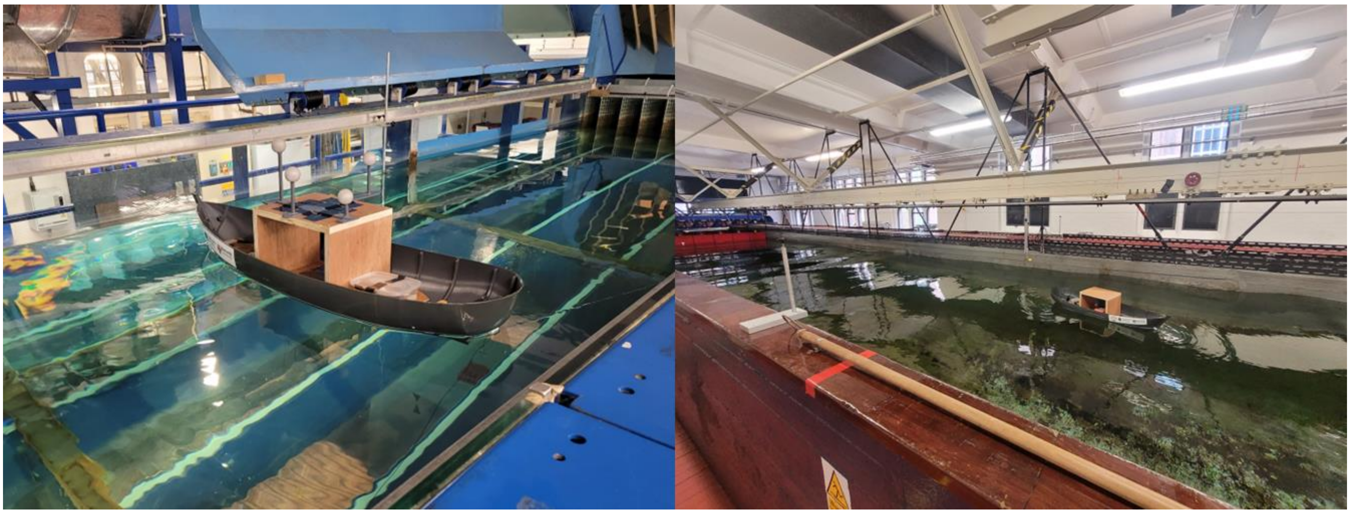

Figure 4: Model in Testing Facilities, Newcastle University. Wind Wave Current Tank (left), Towing Tank (right)

Full-Scale Tests

The vessel used for the full-scale pilot study was an Arran 16 displacement hulled boat, as seen in Figure 5 with particulars shown in Table 4 (Arran Boats, 2023).

Table 4: Arran 16 Particulars

Vessel Particular	Value
Length [metres]	4.88
Beam [metres]	1.98
Draft [metres]	0.30

Figure 5: Arran 16 used for full scale testing.

The full-scale tests were completed in Beadnell Harbour, Northumberland, UK in August 2023. The vessel was moored at bow and stern. The weather conditions were mild with a gentle breeze and small waves, as can be observed in Figure 5. The tide was continuously coming in during the tests. The boat was set up for deployment of marker buoys and contained several inflatables and anchors. The outboard engine was not fitted.

RESULTS AND DISCUSSION

The first stage of testing was to complete inclining and roll decay tests for the model in the 3 different loading conditions. This allowed validation for the results from wave testing. The inclining tests and roll tests were repeated before further phases of testing to ensure consistency of positions throughout. The model testing was divided into 2 phases, the first phase tested the device in regular waves using a commercial motion tracking system (Qualisys) as a baseline to investigate the accuracy of motion data collected from the device. The second phase tested the device in irregular waves with the aim of highlighting the natural roll frequency of the model. The final stage of testing presented is a full-scale pilot study, showing the validity of the methodology at full scale.

Model Scale Inclining Tests

Inclining tests were completed in a small basin using a standard approach. The model was loaded in the three different weight positions as described previously (Figure 3). Four small inclining weights of 200 grams were added and 5 repeats were carried out for each position. The device was used alongside a separate digital inclinometer for validation. The average GM was calculated and is shown in Table 5. The radius of gyration, k_{xx} , was estimated at 0.135 metres using Equation 2. The values for GM and k_{xx} were used in Equation 1 to estimate the roll frequency for each weight position.

Table 5: Inclining Tests and Roll Period

Weight Position	Displacement [kg]	k_{xx} [mm]	GM from Inclining Test [mm]	Roll Frequency (Estimated) [Hz]	Roll Frequency (Measured) [Hz]
Low	17.8	135.2	85*	1.08	1.10
Mid	17.8	135.2	83	1.06	1.04
High	17.8	135.2	68	0.96	0.98

*The models low position GM value was slightly changed from the WWCT tests (WWCT: 0.086m, TT: 0.085m) due to changes to the device setup, namely a new battery and case however the positioning of the weights was the same.

Roll decay tests were completed by exciting the model from the port side by pushing down, when the roll was sufficient, data collection was started, and the roll motion was allowed to decay. This was repeated 5 times ensuring that each decay test produced 5 complete oscillations. The data was collected using the device to record the roll periods and verified with a stopwatch. The device then produced an FFT plot and the roll frequency presented as the 'Roll Frequency (Measured)' in Table 5. An example of one of the roll period tests with plots of the roll angle and FFT is shown in Figure 6.

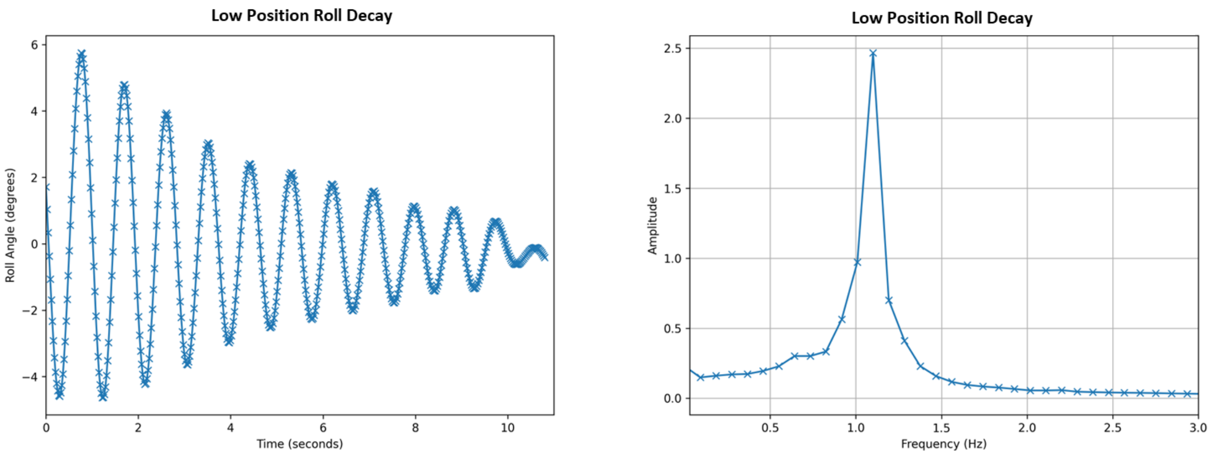

Figure 6: Roll Decay Test Results for Low Position. Roll angle (left) and FFT plot showing roll frequency of 1.10Hz (right)

The results of the inclining and roll tests show that the measured roll frequency is within a window of the estimated roll frequency and the device can pick up changes of GM in model scale. As seen in Figure 3, the difference between the Low and Mid positions is 60mm, under a third of that between the Low and High (210mm) representing a 2.4% and 20.0% reduction of GM respectively. For the change between the Low and the Mid positions the device did not produce a clean enough signal to say with certainty that the device could pick up slight changes of GM. However, the difference between the Low and High positions was clear and the measured roll periods reflected the estimated roll period and showed an evident change in the stability condition of the vessel.

Model Scale Wave Tests: Phase 1

The purpose of Phase 1 was to investigate the accuracy of data capture from the device in comparison to a commercial system. The Wind Wave Current Tank (WWCT) at Newcastle University was selected for this first phase of testing. This allows testing in a wide range of regular waves. The WWCT has a commercial motion capture system, Qualisys, that records the vessel motion through the tracking of 4 reflective spherical targets using 2 cameras set at either end of the test area.

The vessel was placed in 'Low' position and moored in the tank as shown in Figure 7. The GM was calculated at 0.086m from inclining tests conducted at the beginning of testing. The expected roll frequency for this setup was 1.08Hz.

The model used is of a vessel designed for use on the Kenyan coast and for ocean-going trips, so it is likely to encounter a range of operating conditions from calm inshore waters into the Indian Ocean and subject to heavy seas. A test matrix made up of 9 regular waves was selected and is shown in Table 6. These waves were chosen to represent a scaled representation of the wave heights and frequencies that the full-scale vessel is likely to encounter. All the waves tested are shown in Table 6 with the ratios of wavelength over the model water line length and breadth of the model. The wave lengths were measured in the centre of the tank test area where the model was located. The results of 3 of these tests (indicated by *) are presented in Figure 8 with the nominal waves.

Table 6: Phase 1 Test Matrix showing nominal wave frequency and height alongside ratios of wave length to model waterline length and breadth

Wave Frequency [Hz]	Wave Height [m]	Wave Length/L_{WL_model}	Wave Length/B_{model}
* 0.8	0.01	2.69	8.46
0.8	0.02	2.49	7.83
0.8	0.03	2.39	7.53
1.0	0.01	1.48	4.64
* 1.0	0.02	1.55	4.87
1.0	0.03	1.69	5.33
1.25	0.01	0.98	3.10
1.25	0.02	1.02	3.19
* 1.25	0.03	1.05	3.29

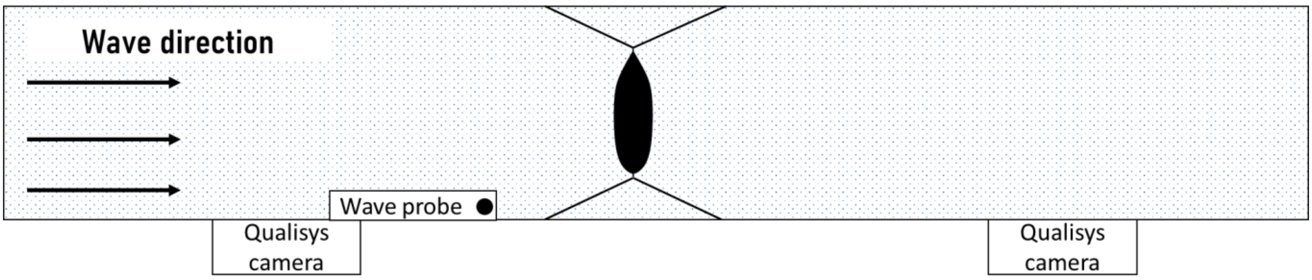

Figure 7: Scaled plan view of the test setup in the Wind Wave Current Tank.

The vessel was placed at beam seas and moored from the bow and stern to 4 points on the tank. The sampling rate of the device was set to 33Hz and the data collection was started remotely through a VNC server to start it simultaneously with Qualisys and the wave probe.

FFT analysis was carried out on the data collected by both the device and Qualisys. The peak frequencies for the tests are shown in Figure 8. The model's motion was entirely dominated by the wave frequency. As can be seen in Figure 8 there was no significant difference between the nominal wave frequency and the recorded peak frequency for both the device and Qualisys, with the peak nominal wave frequencies being 0.8 Hertz (8a, 8d), 1.0 Hertz (8b, 8e) and 1.25 Hertz (8c, 8f). For each of these, the vessel roll frequency is the same as the wave frequency.

Most notably, Figure 8 shows the alignment of the two data acquisition methods, with the device showing peaks at the same frequency and with comparable clarity to Qualisys. The data from the device has greater amounts of noise surrounding the peaks, however this noise is remains low relative to the amplitude of the peak. This noise is due to several factors: lower fidelity raw data from the device, the effect of electrical noise from the environment, greater amount of processing of raw device data and lower sampling rate of the device in comparison to Qualisys. These factors are likely the cause of the lower peak amplitude seen in the FFT from data collected by the device. The effect of the reduced sampling frequency should be diminished at full scale due to the longer roll periods resulting in a higher number of data points per roll period giving greater definition then at model scale.

Overall, the results from the WWCT show there is no significant difference between the two acquisition methods with both detecting the same peak frequencies. The signal using lower fidelity data produces lower amplitude peaks with more noise however the effect of this is minimal as the peaks are easily identifiable, showing the validity of the device methodology. The first phse of the model scale testing ensured the accuracy of the data produced by the device, the second phase builds upon this to identify the natural roll period using irregular waves and more complex wave spectra.

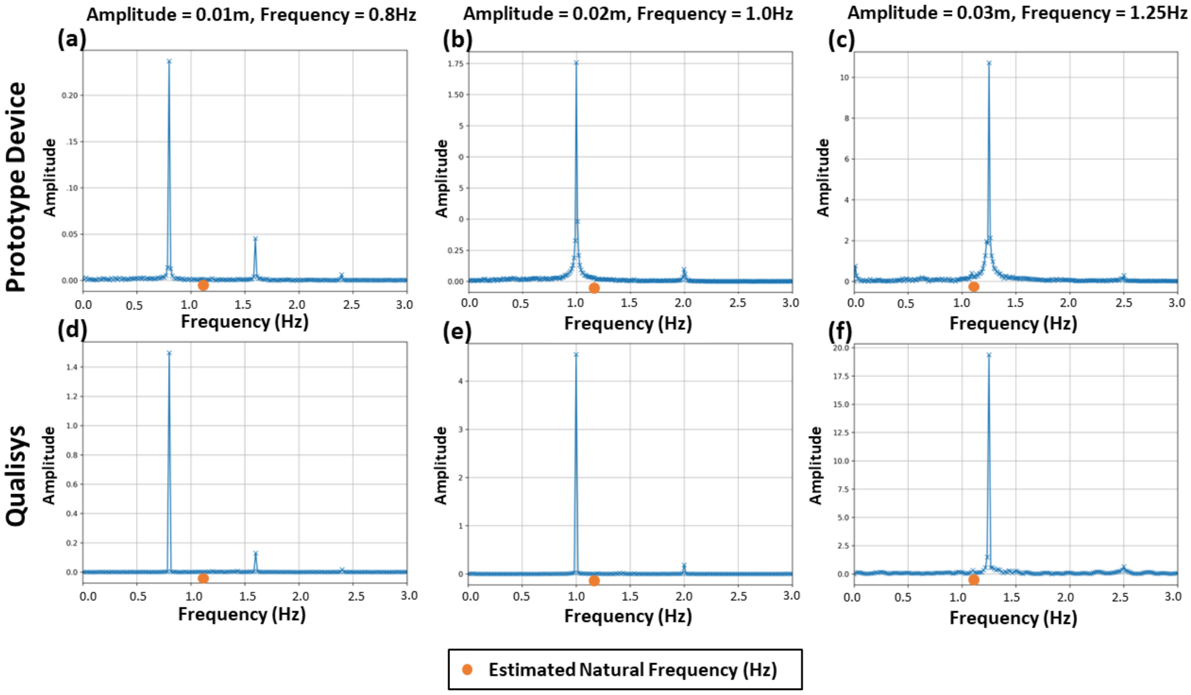

Figure 8: Comparison of FFT graphs for the two acquisition methods, the prototype device (a, b, c) and Qualisys (d, e, f) for a sample of 3 nominal sine waves described in Table 7. The estimated natural frequency is denoted by the orange dot above the x axis for each subplot.

Table 7: Nominal and Recorded Wave Data

Nominal Wave		Average Recorded Wave Probe Data		Subplots in Fig.8
Amplitude [m]	Frequency [Hz]	Amplitude [m]	Frequency [Hz]	-
0.010	0.800	0.010	0.800	a, d
0.020	1.000	0.013	1.000	b, e
0.030	1.250	0.039	1.249	c, f

Model Scale Wave Tests: Phase 2

The Towing Tank at Newcastle University was selected for the second phase of model testing due to the greater length and breadth of the test area. Initially, the model was moored first in 4-point mooring in beam seas as in the WWCT and regular waves were used. As these results were consistent with the WWCT it could be said that the difference made by the tank size was minimal. The vessel was then modelled as being ‘at anchor’ using a mooring line attached to a lead weight at the bottom of the towing tank, this mooring line was measured to ensure that the model vessel would not be able to make contact with the sides of the towing tank, the set up can be seen in Figure 9.

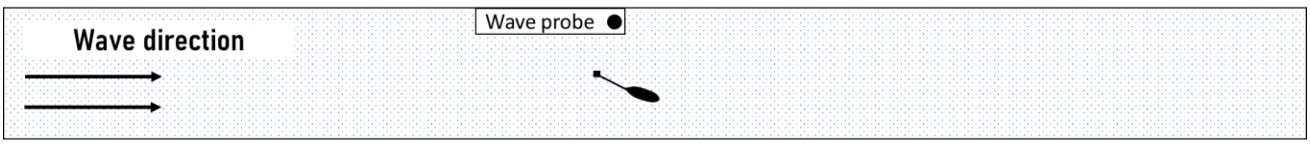

Figure 9: Scaled plan view of the test setup in the Towing Tank.

The intention in the second phase was to create more complex wave forms and allow waves to disperse over the tank length and mix, for this reason the test duration was also extended to 20 minutes. Two quasi wave spectra were created using combinations of wave fronts, sine waves, modified JONSWAP spectra and white noise, and are presented below in Figure 10a, &10b, denoted by Wave 1 and Wave 2.

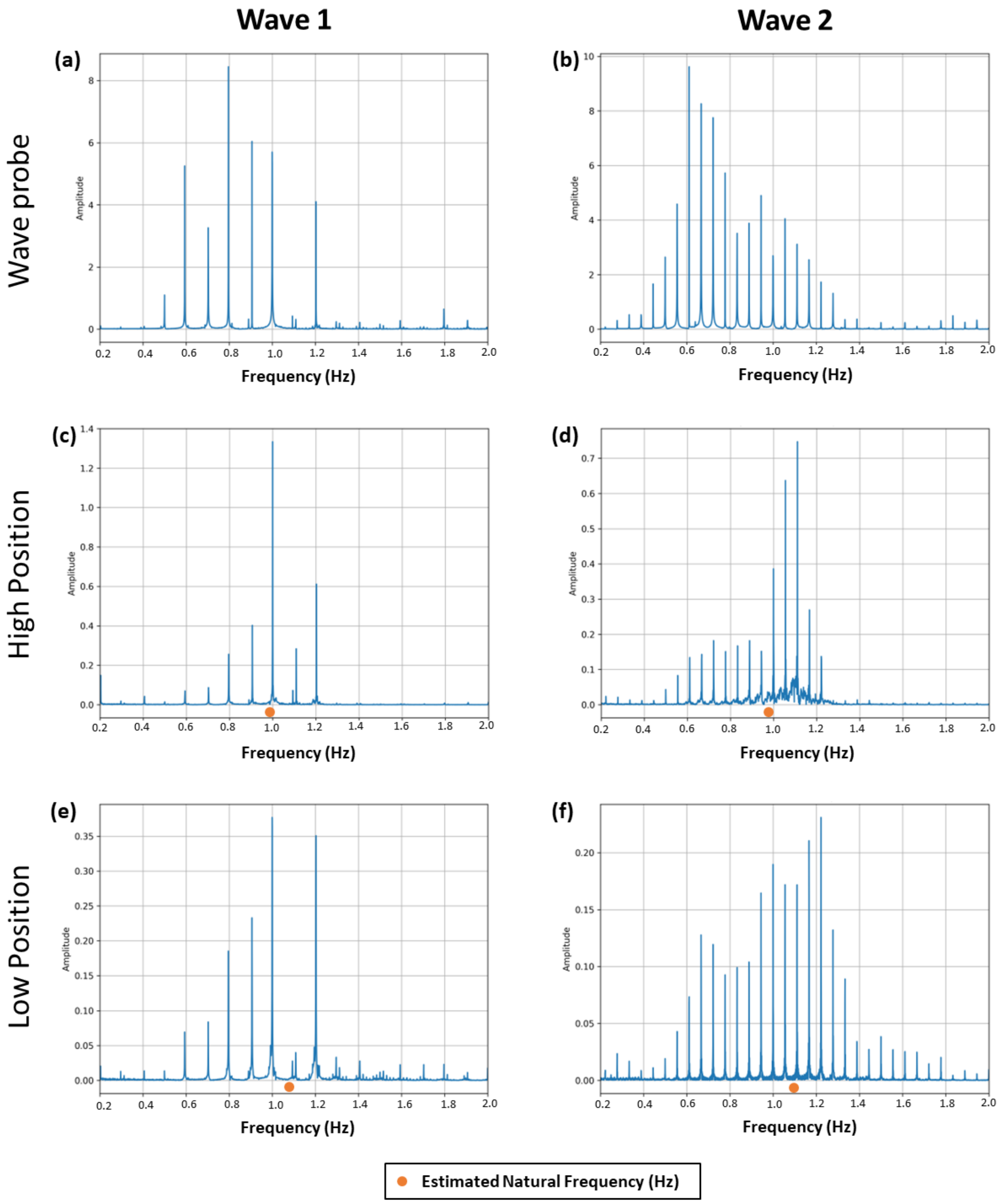

Figure 10: FFT results from Phase 2 testing. The 2 quasi wave spectra: Wave 1 (a) and Wave 2 (b) are shown with the vessel motion for each Wave 1 (c, e) and Wave 2 (d, f). The estimated natural frequency is denoted by the orange dot above the x axis for each subplot.

The model setup remained the same as in Phase 1of model testing and the model was tested in 2 of the loading conditions shown in Figure 3:

- Low Position: Weight on vessel deck (GM: 85mm, estimated roll frequency: 1.08Hz)
- High Position: Weight on top of second deck (GM: 68mm, estimated roll frequency: 0.96 Hz)

Figure 10 shows the FFT analysis of the model roll motion analysis data for the 2 loading conditions; high (10c, d) and low (10e, f) for 2 wave spectra; Wave 1 (10a, c, e) and Wave 2 (10b, d, f). The FFT plots for the vessel roll motion (10c-f) are shown alongside the FFT plots for the wave probe data (10a, b). The estimated natural roll frequencies for each position are denoted by the orange dot above the x axis.

Looking at the data from Wave 1 (Figure 10, left), initially it appears the natural roll frequency has been picked up for the high position, as there is a clear peak at 1.0Hz and roll frequency estimated at 0.96Hz and measured at 0.98 Hz from roll decay tests. However, as the same frequency of 1.0Hz is also the peak frequency in the low position it is clear this is a vessel response to the wave frequency.

For the more complex wave, Wave 2 (Figure 10, right) again the natural frequency of the vessel is not clear. The highest amplitudes seen are around 1.1Hz for the High position and 1.2 Hz for the Low position, around 0.1 Hz higher than the estimated roll frequency. The data recorded on the device across all tests has a negative skew whereas both waves have a positive skew. This shows general shift away from vessel motion being dominated by the wave frequencies in the Towing Tank in comparison to the Wind Wave Current Tank. Although the peak frequencies had moved away from the wave frequencies the two could not be said to be independent of each other, this is more evident in the more complex wave, W2.

Across all 4 tests the FFT plots have a more similar shape for each wave rather than each position suggesting the wave frequencies have far greater affect in the model than the weight position. This suggests the results from the towing tank show a continuation of issues faced in the Wind Wave Current Tank, with the natural roll frequency not being seen in continuous monitoring of the vessel motion. As this may be due to unrepresentative conditions using unidirectional waves a small pilot study was conducted.

Full Scale Tests

A pilot study was conducted at full scale using a vessel in the local area to investigate whether issues present in model scale would still present at full scale. To test this a series of tests were conducted, each with a duration of 5 minutes, allowing different loading conditions to be assessed. The vessel used was a 4.88 metre Arran 16, described previously in Table 4. The vessel was moored on a beach at bow and stern in a similar fashion to the mooring lines used in first phase of model testing. During the testing the tide was continually coming in and there were slight changes in the wind and waves during the time of testing, but both remained calm.

The peak frequency over time graphs are shown for the following tests in Figure 11:

- Test 1: 2 people in vessel (Added Weight: 130kg), walking around vessel randomly.
- Test 2: 2 people in vessel (Added Weight: 130kg), rocking vessel to create constant roll motion.
- Test 3: Vessel empty, vessel allowed to roll freely.
- Test 4: Vessel empty, constant roll motion induced externally.

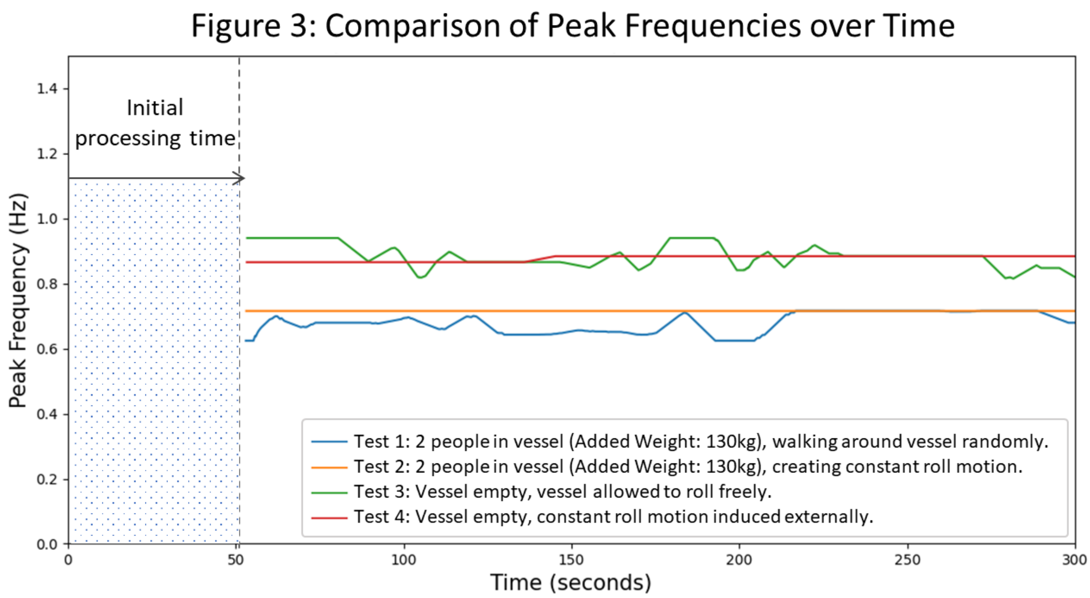

Figure 11: Comparison of peak frequencies over time for 4 test conditions.

The peak frequency found from the FFT analysis is plotted against time in Figure 11, with the FFT using a 50 second 'window' of data, updating itself every 10 seconds. No significant change in peak frequency within each test was expected to be seen as test conditions remained stable and no change in the position of the centre of gravity, G, was made. Although there is variation in the peak frequency detected, there remains a clear difference between the two loading conditions, with

Tests 1 and 2 having a roll frequency of around 0.7 Hz and Tests 3 and 4 around 0.9 Hz. As can be expected the Tests 2 and 4, where roll motion was constant, had almost no change in recorded roll frequency. For Tests 1 and 3 there is expected to be a greater effect of environmental conditions such as wind and waves and this is reflected in Figure 11, where both tests have more variation of recorded peak frequency in comparison to Tests 2 and 4. The results from these tests showed a clear difference between peak frequencies for the 2 loading conditions and the device was able to pick up differences between these, as well as pick up peak frequencies clearly out of laboratory conditions dealing with the effects of waves, wind and tidal currents.
This pilot study showed that the device could collect and process roll data for a full-scale vessel to a sufficient level of accuracy. Therefore, the device shows potential for use on fishing vessels in small scale and subsistence fishing, where there is a need for lower cost devices.

CONCLUSIONS

This project has laid the foundations for further work investigating how low-cost digital technology can be used to assess the stability of fishing vessels in artisanal settings. The results of a prototype device have been presented from both model and full-scale testing.

The first phase of model testing has shown that low fidelity data can be used to measure roll motion in a comparable fashion to a commercial system. However, in regular waves unrepresentative of ocean waves the natural roll frequency of the model was not detected. The second phase of model testing aimed to create more realistic waves through quasi wave spectra, the vessel motion here was a clear response to the waves rather than simply reflecting the wave frequencies however this still did not allow the natural roll frequency to be detected.

The full-scale pilot study was successful in detecting the natural roll frequencies of the vessel and detecting changes in the roll frequency and therefore the vessel GM. Although work to refine the model scale testing remains, the results from full-scale tests are promising, demonstrating real-life applications. While further development is needed to make a full functioning device for everyday use, this study has effectively demonstrated proof of concept.

FUTURE WORK

Further work into model testing should take place to resolve issues around wave frequency domination and investigation into the minimum value of GM before the stability condition of the vessel becomes dangerous should be carried out to determine alert levels for the device.

Full-scale testing is planned to take place on a traditional East African fishing boats and complete stability testing will also be carried out. This will include an inclining test and full lines plan. Alongside this the device should be used in its inclining test feature and then using the roll test to investigate error margins between a comprehensive stability test and this device.

Further development of the prototype device with a more user-friendly Graphical User Interface (GUI) will take place, whilst also investigating the potential to integrate the proposed technology and algorithms into regular smartphones. These are increasingly owned and used by fishers, and provide an opportunity to efficiently implement the technology. However, there are anticipated difficulties in the use of a smartphone which may include the robustness of the sensor architecture and setting a steady sampling speed, especially when the phone's processor is completing background operations.

Additionally, the creation of a vessel database to aid understanding of East African fishing boat forms will improve the device algorithms and support improve estimation of key parameters such as displacement and ensure the estimated radius of gyration is suitable.

CONTRIBUTION STATEMENT

Nathan Manojlovic Smith: conceptualization; methodology; investigation; visualisation; writing – original draft. **Priscila Melo:** supervision; visualisation; writing – review and editing. **Simon Benson**: conceptualization; project administration; supervision; writing – review and editing.

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