A FREE RUNNING INSTRUMENTED CONTAINER SHIP MODEL FOR INVESTIGATING ENERGY EFFICIENCY IN WAVES

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As the shipping sector faces up to the challenge of decarbonisation there is an urgent need to increase the energy efficiency of ships. Improved design will need the synthesis of computational, experimental and analytical approaches to the investigation of ship powering. While there has been a significant emphasis on improvements to the use of computational simulations there is an equivalent need to enhance the quality of measurements and insights that can be gained from towing tank tests. To this end an instrumented geosim of the KCS hull form has been built and representative results from four test campaigns are presented. The synchronised measurements of wave environment, model motions, hull forces and moments, propeller thrust and torque as well as rudder forces and moments allows time accurate performance to be understood rather than just mean behaviour. This gives much greater insight into the physics of the interaction between hull, propeller and rudder as well as how that influences the power demand and overall voyage energy.

Keywords: hull-propeller-rudder interaction; energy efficiency; synchronized measurements; wind assisted shipping; power demand fluctuations

1. Introduction

As ever higher aspirations for ship propulsive energy efficiency are required, as part of the need to reduce the greenhouse gas emissions of shipping, a deeper understanding is required into the hydrodynamic behaviour of ships in waves[1]. A key aspect is the complex interaction at the stern of a vessel between its propulsors, manoeuvring devices and the wake flow. Conventional design has typically focused on optimising performance at a single design speed in calm water with the use of suitable power margins to account for dynamic effects. The use of computational fluid dynamics (CFD) is well established as part of the ship design cycle. However, there is still a lack of detailed experimental validation data for predicting the dynamic performance of a manoeuvring ship in waves. Similarly with the likely wide adoption of wind assist devices conventional ship designer's need to gain a deeper understanding of the influence of leeway on hull-propeller-rudder interaction.

Conventional tank testing uses a towed scale ship model at zero drift that is just free to heave and pitch. Basic tests are conducted in calm water and for more advanced analysis at a series of regular head and sometimes where possible following waves. Forces and moments are measured and taken as mean values with the added resistance as the difference between the calm and wave condition. Deeper understanding of the mechanisms of hull-propeller-rudder interaction and the provision of high-quality data for CFD validation requires synchronized time accurate data for wave height, ship motion, hull forces, propeller rpm, thrust and torque, and rudder forces and moments.

As part of the UK's Clean Maritime Demonstration project programme AMPS-USV a newly built geosim (*3.81 m* LPP) of the Korean Container Ship (KCS)[2] was fitted out with a propeller thrust and torque load cells and rpm encoder, a three-component rudder dynamometer, and a six degree of freedom inertial measurement unit. Data acquisition (250Hz), propeller rpm and rudder heading control are achieved using two on-board microPX PCs. At present dynamics settings are controlled using a modified radio control unit with the system enabled for eventual autonomous control. The KCS model can be tested either attached to a carriage via a conventional post system or be operated in a free running mode either in towing tanks, model basins or lake environments.

The development process of the test programme for this model will be reported capturing relevant data from four test campaigns:

- Comparison tests with KCS benchmark Geosim calm water resistance data (Feb 2022)
- Experimental uncertainty of time accurate data from laboratory tests of SESS6077 Zero carbon ship resistance and propulsion Master's module (Nov 2022).
- Performance in waves for towed and free running modes (March and Sept 2022).
- Interaction effects of towed model at drift angle with and without waves (Sept 2022 and June 2023).

All the tests were carried out in the University of Southampton Boldrewood tank. This tank, fully commissioned February 2022, is 138 m long, 6 m wide and 3.5 m deep and has a maximum carriage speed of 10 m/s. It is equipped at the west end with 12 independent 0.5 m HR Wallingford wave makers, a passive beach at the east end and a full-length deployable side beach on the south wall. The carriage drive allows up to four tow speeds to be tested per run, a fixed rpm controller can use preset rpm and likewise rudder angles which allows productive use of each test.

The synchronized measurements of motion, propeller, hull and rudder forces effectively capture how the propeller-rudder unit needs to be designed as a whole with changes in propeller operating conditions strongly influenced by rudder angle, ship orientation and wave phase. Example results from the four test campaigns are used to illustrate the depth of understanding and understanding of the uncertainty required for use in validating CFD that are now possible and should be perhaps considered as best practice for experimental testing. This first phase of the model development sit confirm capability for accurate measurements prior to carrying out long duration tests similar to those developed with an earlier tanker model[3].

2. Model Design

Hull

A 1:60.95 scale geosim model of the KCS hull form with specific particulars in Table 1 was manufactured from laser cut plywood frames with strip planks and given a hydrodynamically smooth paint finish. The model has a detachable bow and standard trip studs mounted at 5% of length from bow. The model was towed using a twin post system that used a manufactured plate fitted in the model. This plate allows a range of drift angles to be set between +/- 8deg in 0.5deg intervals. For the drift tests the twin posts are mounted on the towing tank centre-line. As a result the motion of the model is constrained to heave and pitch about the tank centre line rather than the ship axis system. The locations of the posts are given in Figure 1.

Propeller

A high quality finished titanium alloy KP505 propeller was manufactured and used in the self-propelled tests (Table 2, Figure 2). Figure 3 shows the model mounted on the carriage at an angle of drift.

Table 1 Principal dimensions of instrumented KCS model

	Full-scale	Boldrewood KCS
Scale	1.0	60.955
Draft amidships [m]	10.8	0.177
Displacement [tonne]	53384	0.230
LBP [m]	229.7	3.768
LWL [m]	232.5	3.814

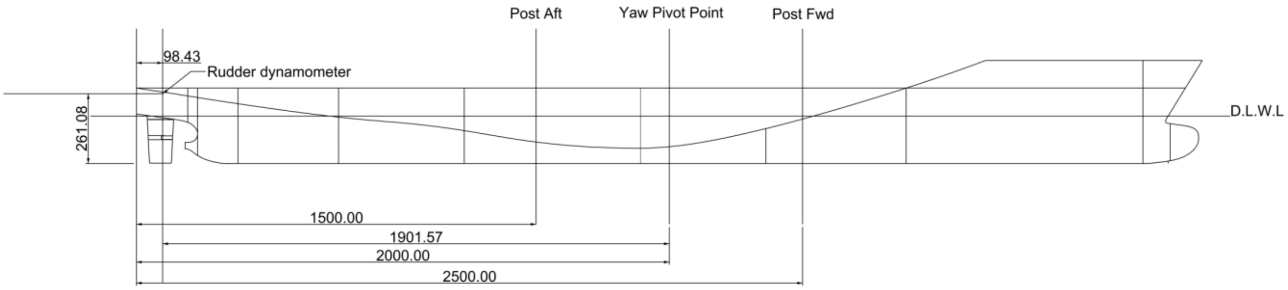


Figure 1 Boldrewood model profile including location of tow posts

Table 2. Key dimensions of KCS propeller

	Full scale	Boldrewood KCS propeller
Scale	1,0	60.9547
Section	NACA66	
Ae/Ao	0.8002	
No. of Blades	5	
Diameter [m]	7.9	0.1296

Figure 2 Close up of model scale five bladed KCS propeller and hub cap

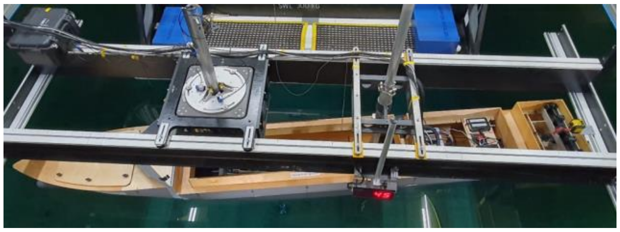


Figure 3 KCS Model mounted at an angle of drift on carriage showing main post dynamometer and moment restraining post

Figure 4 View from aft showing Titanium alloy propeller and all-movable rudder- gap clearance is ~ 1 mm

Rudder

For these experiments a single piece all-movable rudder with the same planform as the original semi-balanced skeg rudder was manufactured (Table 3, Figure 4).

Table 3 All-movable rudder particulars

	Full-scale	Boldrewood KCS model
Scale	1.0	60.9547
Section	NACA0018	
Wetted Area Rudder [m^2]	115	0.0310

Free running capability

As the model was designed to work both when attached to a carriage and in a free running mode it was designed to contain its own power system and control system. The power was provided by two sets of suitably sized Lithium ion batteries to give 8 hours of operation. This allows a full day of testing either in the tank or in a lake/basin. A reaction torque load cell attached to the electric motor casing allows time accurate propeller torque measurement. The motor is mounted on a sliding system that allows propeller thrust to be measured along with an optical sensor to measure RPM. A proportional controller allows the propeller rpm to be set and held constant using a modified radio controller unit.

The ability to control direction when free running requires a suitable rudder controller. This was also provided by a radio control unit with the ability to fix a set (calibrated) value of rudder angle or to vary. The system is designed to be upgraded in the future to allow fully autonomous operation.

3. Data Acquisition

The need to acquire high resolution time accurate data influenced the choice of a 250 Hz data acquisition rate**.** Three separate systems are used. An onboard system that is capable of capturing 16 channels with flexibility in what data sources are acquired. Data acquisition (DA) for specific runs is controlled from one of the on-board micro-PC systems via a remote desktop connection. The other micro-PC controls the data acquisition of a nine degree of freedom inertial measurement unit (IMU). These measure translational and rotational accelerations as well as orientation using a magnetometer.

The towing tank dynamometer was designed and manufactured for the tank facility by the University of Southampton's Wolfson Unit for Marine Technology and Industrial Aerodynamics. It can measure six components of force/moment. For these tests of interest are the drag, side-force and yaw moment. As two posts were used an additional force block was mounted at the foot of the guide-post. This is designed to just measure side-force and present no resistance in the drag direction. Further details are given in [4] along with the laser-based system to measure carriage position and speed. Heave and pitch sensors as well as a wave elevation ultrasonic sensor mounted near the front of the carriage at 1/3rd of the carriage width. The carriage-based data acquisition system also has 16 channels and includes the position and speed of the carriage.

The low force levels expected on the rudder required the purchase of a specific Force-Torque sensor from ATI Industrial Automation. The dynamometer is mounted on the deck in a waterproof housing and connected to the rudder via a shaft. A servo controller and angle position sensor controlled via the radio control unit allows the rudder angle to be set remotely. Typically for the tests carried out it was possible to make measurements of three or four rudder angles per run. The rudder dynamometer was only available for the final three days of testing in June 2023. A supplied calibration and interaction matrix allows six components to be measured of which the side-force, drag and yaw moment are of the most interest although the x and y axis moments allow the centre of pressure spanwise to be found.

A challenge for use of complementary DA systems is the need to synchronise their acquisition. When the model is attached to the carriage the onboard and a carriage system can be locked together by splitting a cable and acquiring same signal system on both. It is harder with the IMU, however, it can be inferred from the x-axis acceleration and propeller measurements. When the rudder angle is not acquired changes in angle when attached to the carriage can be seen as the side-force varies on both the rudder dynamometer as well as the hull side-force channels.

The wave elevation provides detail of the onset wave condition. These are programmed from the carriage. Tests have been carried out in head and following seas. For head seas a wave system is created and progresses along the tank. As the wave train approaches the beach end either the carriage-motion commences or the free running model is accelerated to test speed. For the free running tests calibration runs were carried out to find the average model speed so that carriage and model can maintain the same relative position. It was found that the model operator could maintain a consistent track along the tank centreline with deviation in lateral acceleration acquired from the IMU.

4. Data Analysis

Typically for a test run up to three data run text files are recorded – on-board(LASSO), carriage (NI) and motion (IMU). As data is acquired for a period of time, that at least covers the whole length of the carriage or model run, the first phase of analysis requires the data to be separated into specific test segments. The carriage controller allows up to four carriage speeds to be run as the model progresses down the tank. Other potential variations for a carriage test are changes in propeller RPM or rudder angle. Data that should be excluded is where any of these (speed, RPM, angle) is in transition. The initial start and finish phases when the model is at rest again can also provide useful checks of ‘zero’ load conditions.

As one of the uses of the instrumented model is for education no automatic data acquisition is provide but rather students are provided with a basic toolkit of python routines and an associated Juypter notebook environment so they can study the influence of various filters and processes for processing the data. This environment allows a much deeper appreciation of the quality and measurement errors associated with a particular data set. Python scripts facilitate automated processing and data presentation of comparisons. Conventional acquisitions systems often just record data when the operator has deemed that steady conditions have been reached.

The data acquired has implicit filtering from the 250 Hz acquisition and analogue to digital conversion. Once the run segments have been identified from their start/finish times the frequency content of the signal provides significant insight into the behaviour of the dynamometer system.

5. Test Campaigns

For all the test programmes carried out a common procedure has been followed. The model has been ballasted to its design draft. There are slight variations in ballast locations required depending on the instrumentation systems used. For instance, the drift angle tests include an attachment plate. Tests usually take place over 2-to-5 day tank bookings. Such tests have taken place in February, March, September and November 2022 as well as the most recent in June 2023. Representative results are included from these tests associated with the four campaigns. After each set of tests, the systems were further refined. The most significant change was the first use of the rudder dynamometer in the June ’23.

Resistance Comparison for KCS

One of the reasons the KCS was chosen as the hull to develop for the Boldrewood tank was that it would allow comparison with the test results acquired for over decades in support of International Towing Tank Conference (ITTC) inspired CFD validation workshops. Figure 6 compares the resistance values in calm water for the three most recent tests with an appropriately scaled set of data from the Tokyo 2015 CFD workshop dataset[2]. The typical differences are 2% with the largest being due to some uncertainty with the precision of the ballasting for the student laboratories in November 2022

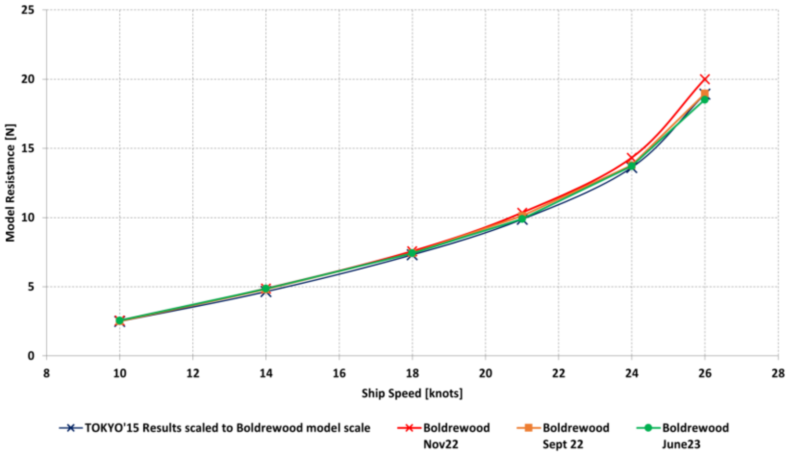


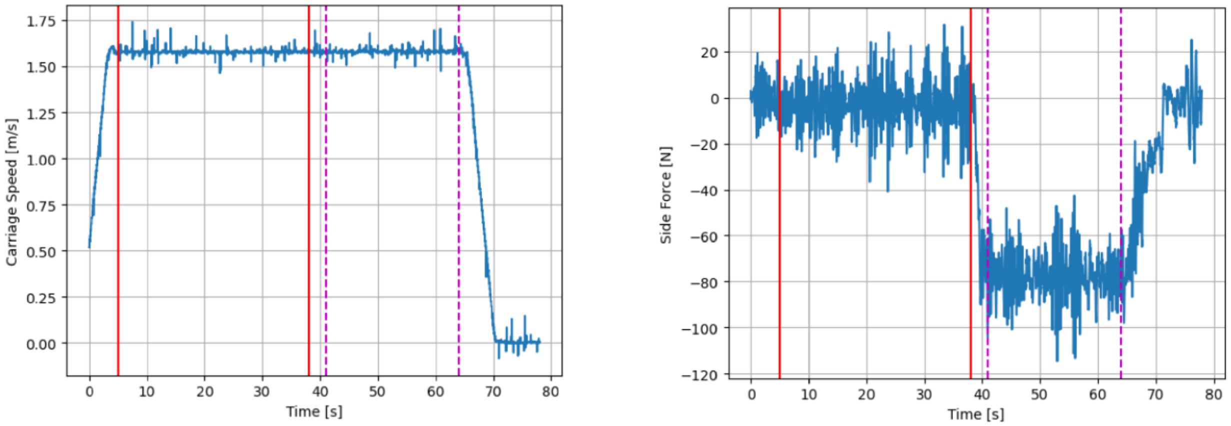
Figure 6 KCS model resistance comparison corrected to water at 15 deg C [B]

Experimental uncertainty from student laboratory tests

The aim of the KCS powering laboratory in the SESS6077 Zero carbon ship resistance and propulsion module is to investigate the influence of signal processing and other uncertainty factors on the experimental determination of ship powering performance from an experimental test run. Students work in groups of six over a two-hour period. In Nov ‘ 22 a variety of tests were carried out:

(I) Baseline calm water resistance tests with rudder set at either zero or 20 degrees
(II) Self propulsion tests at speed close to design for a variety of rpm and rudder angles of 0 and 20 degrees.
(III) Self propulsion tests at speed close to design in regular waves and rudder angles of 0 and 20 degrees.
(IV) Self propulsion tests at speed close to design in regular waves and rudder angles of 0 and 20 degrees.

Figure 7 illustrates the process of dividing run segments for rudder angle changes. For these tests the propeller was operating at 956 RPM, and the model was operating in waves with a frequency of 0.798 Hz and amplitude of 0.019m and carriage speed of 1.58 m/s.



(a) Carriage speed (b) Side force

Figure 7 Plots taken from a specific student assignment showing identification of two phases of a single tests corresponding to rudder angles of 0 and 20 deg. Both sets of data are raw eg unfiltered.

Table 4 gives the student derived mean, variance and uncertainty for the carriage set of measurements. The large variance is associated with the wave induced motion which influences the thrust and torque as well as the drag in waves. The corresponding uncertainties for the non-dimensional parameters are shown in Table 5.

Table 4 Mean values and Type A uncertainties for measurements made in student assigned runs 1 and 2

Parameter	**Run Number**	**Arithmetic Mean**	**Variance**	**Standard Uncertainty**
Water Temperature [degrees]	Run 1 and 2	17.4	0.798	0.0304
Propeller Thrust [N]	Run 1	16.691	0.13314	0.0063624
	Run 2	17.338	0.14998	0.39981
Propeller Torque [N]	Run 1	0.343	8.80E-05	0.000164
	Run 2	0.352	9.98E-05	0.000207
RPM	Run 1	955.872	751.751	0.478085
	Run 2	956.700	608.146	0.511768
Carriage Speed [m/s]	Run 1	1.578	7.499	0.0001510
	Run 2	1.580	7.737	0.0001825
Drag [N]	Run 1	0.770	453	0.371
	Run 2	1.393	371.2	0.3998
Side Force [N]	Run 1	-3.252	104.4	0.1782
	Run 2	-77.769	101.0	0.2085
Heave [mm]	Run 1	-7.777	2.300	0.02645
	Run 2	-7.675	3.057	0.03628
Trim [mm]	Run 1	0.666	0.373	0.0107
	Run 2	0.430	0.336	0.0120

Table 5 Non-dimensional parameter uncertainties. Note these are high because the response of the ship is periodic with the wave field encountered

		K_T	**K_Q**	**Re**	**Fn**	**C_T**	**C_L**
Run 1		0.231	0.0364	5555000	0.2582	0.00554	0.0
Run 2		0.239	0.0373	5562000	0.2586	0.00593	0.0236
Type		Type A	Type A	Type A	Type A	Type A	Type A
Standard Uncertainty	**Run 1**	0.6761	0.6761	0.000151	0.000151	0.3710	0.000214
	Run 2	0.8268	0.7237	0.000183	0.000183	0.3998	0.000258

Powering performance in waves

The powering trials with the KCS were undertaken as part of a study to investigate how ship motions might influence the performance of fuel cells for ship propulsion. To do this a series of tests in a variety of regular and irregular seastates in both head and following seas. These were carried out for some initial towed tests, but the main tests focused on free running tests with the rpm set so that the model average speed was at the design speed of 1.58 m/s. The speed could be checked from the encounter frequency.

The performance of the instrumented model for three example conditions are included. Figure 8 and 9 show the self-propelled condition in calm water as a benchmark for the IMU and on-board (LASSO) data respectively. The time signals can be synchronised by the start of the rpm which occurs at 10 seconds on the LASSO and 20 seconds on IMU.

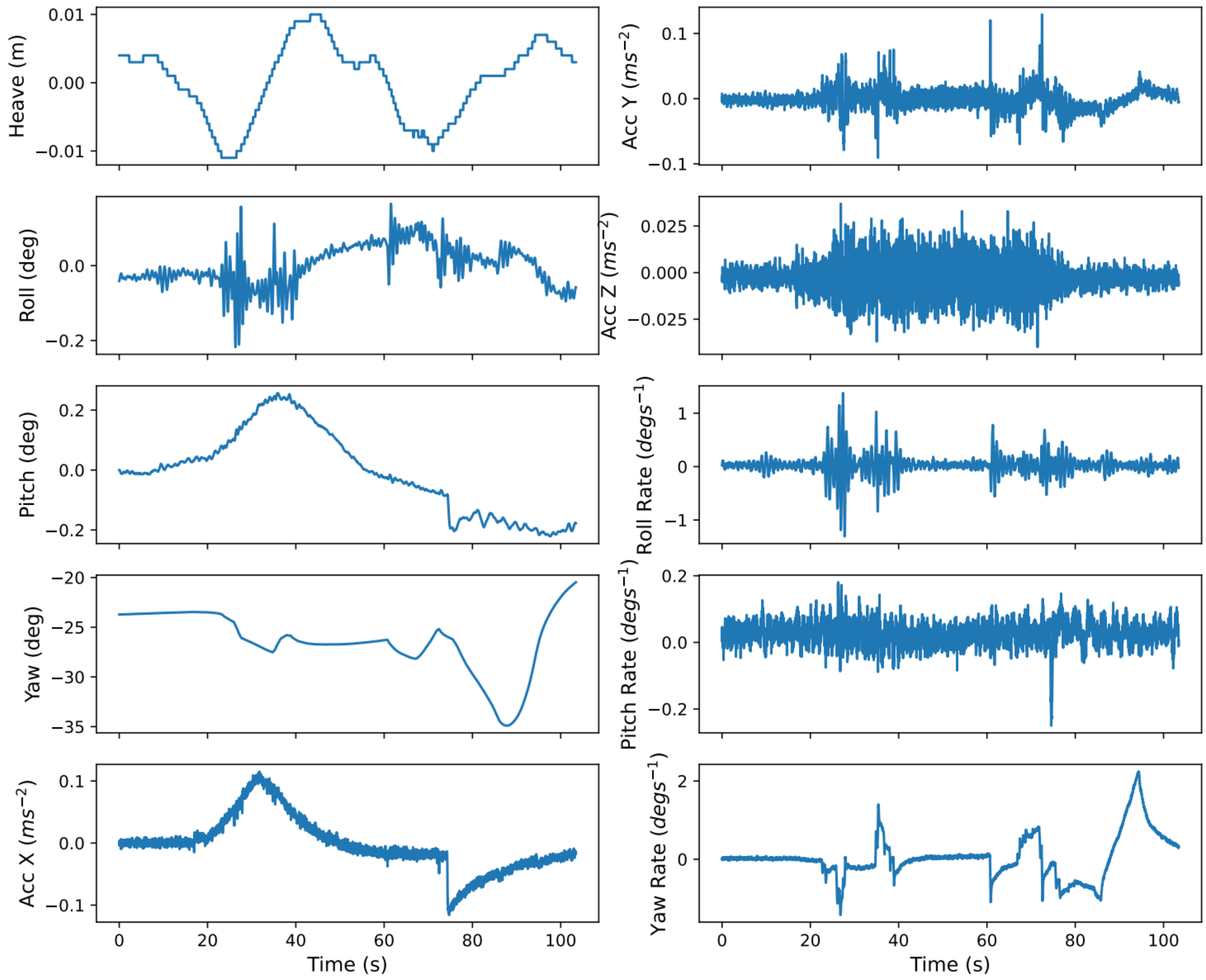


Figure 8 IMU data showing heave, pitch and yaw(course along tank), three translational accelerations and three angular rates for calm water.

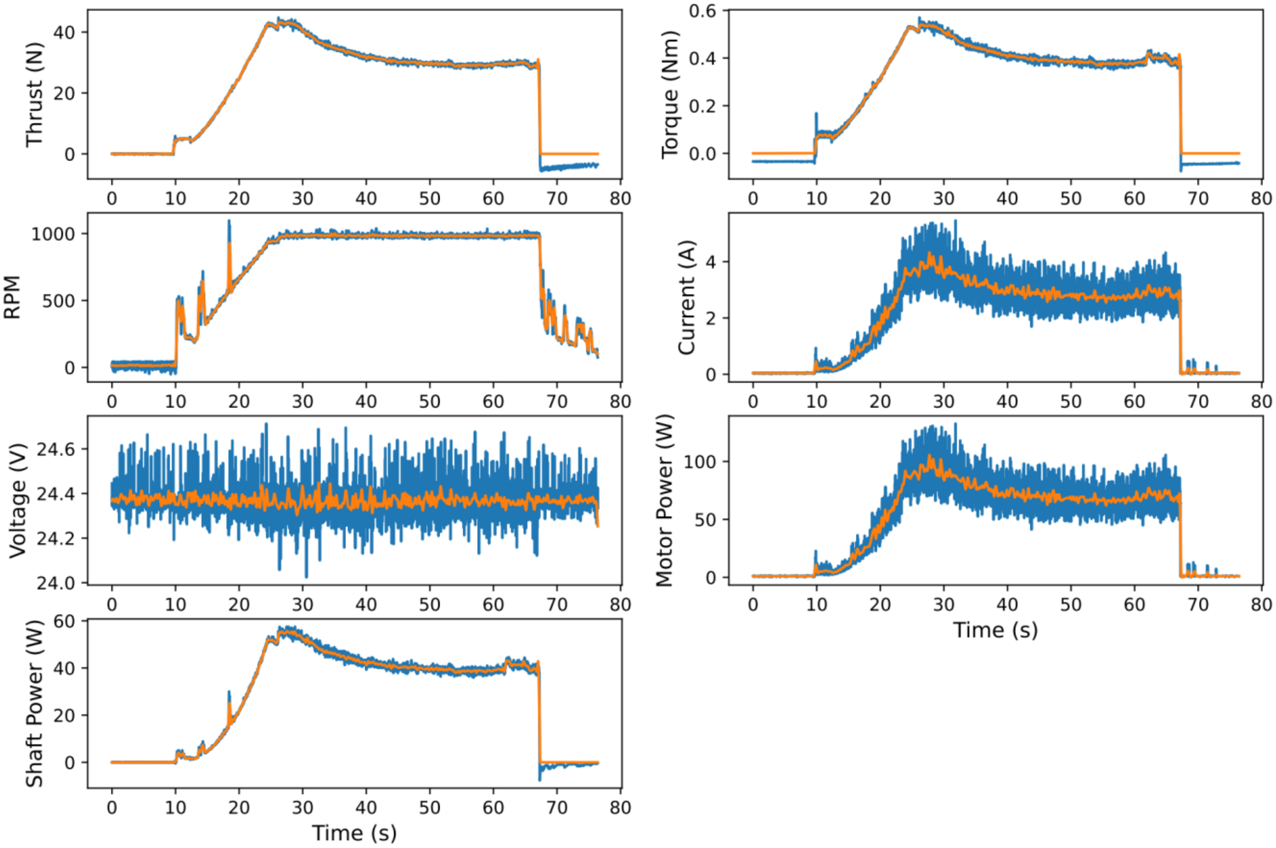


Figure 9 LASSO data for onboard propeller and power including 150 point rolling average to filter high frequency. Constant speed occurs from 50 seconds onwards. Spikes on the rpm are associated with occasional optical system drop out rather than actual changes in rpm.

Figure 10 and 11 and 12 and 13 show IMU and LASSO data respectively for a regular and irregular sea state with the same propeller RPM setting. It is clear that these data sets are rich in detail. For instance, the performance of the human operator in course keeping can be seen in the alterations in yaw. The regular sea state has a short wave length compared to the model scale and so has only a limited influence on the motion and power response. Whereas in the following sea the spectra of wave lengths induces greater motions and power fluctuations. Such fluctuations in power demand will induce losses of efficiency in power supply system be that fuel cell or in this case battery. It also suggests that improved propulsion control should be possible with controllers that can predict the likely seastate variation .

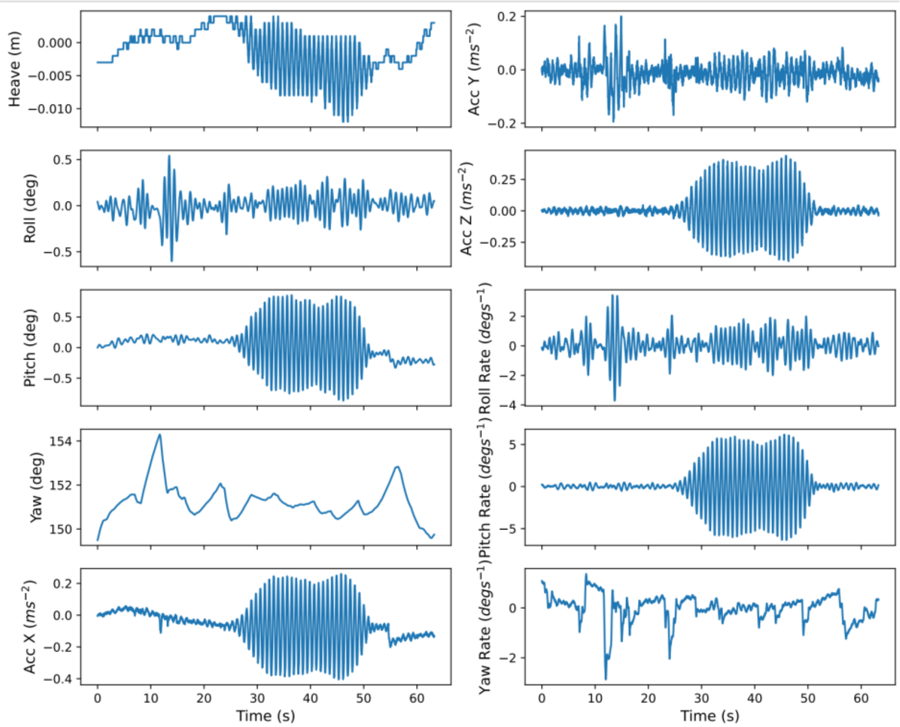


Figure 10 IMU data to show how motions vary with sea state for constant RPM: Run 47 Regular Head Sea

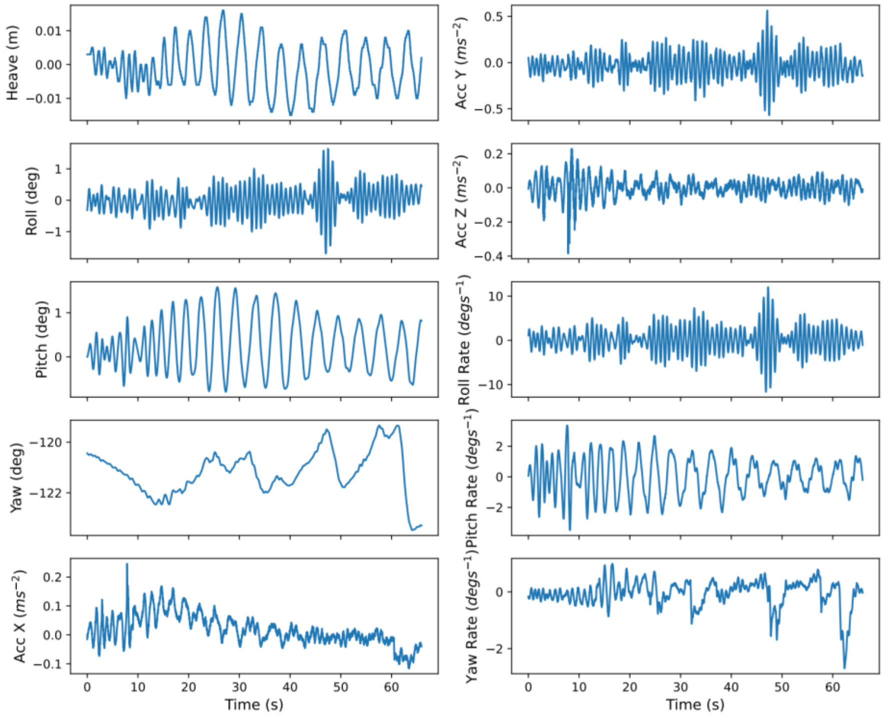


Figure 11 IMU data to show how motions vary with seastate for constant RPM: Run 54 Irregular following sea

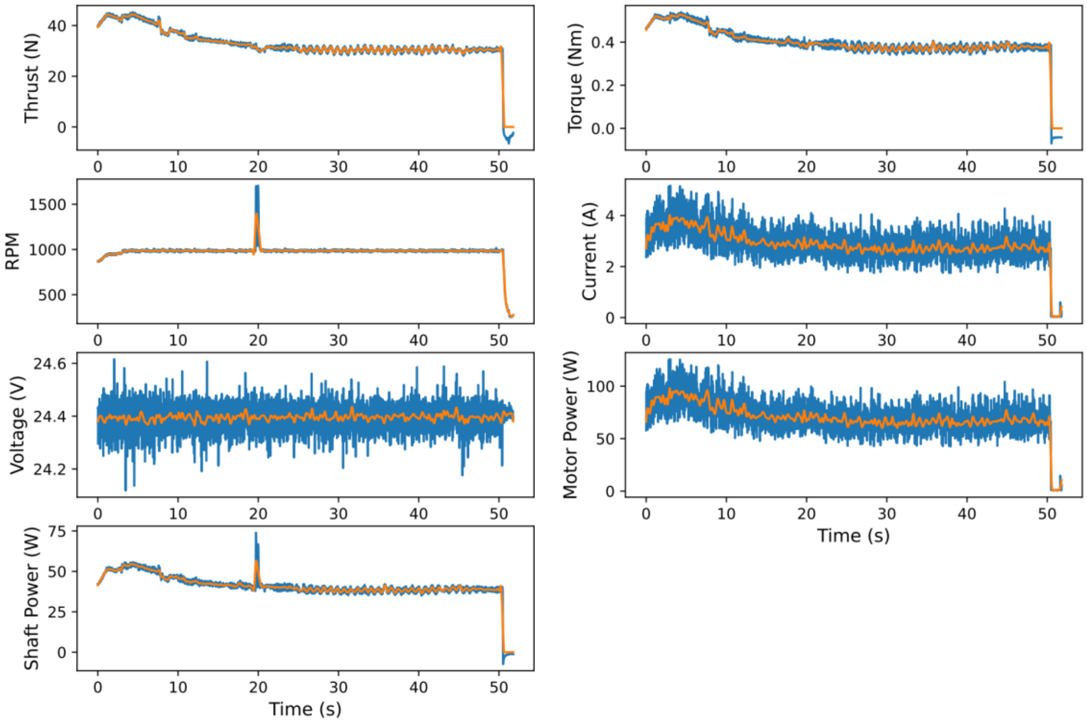


Figure 12 LASSO data showing how power variation changes with seastate for constant RPM: Run 47 regular head sea

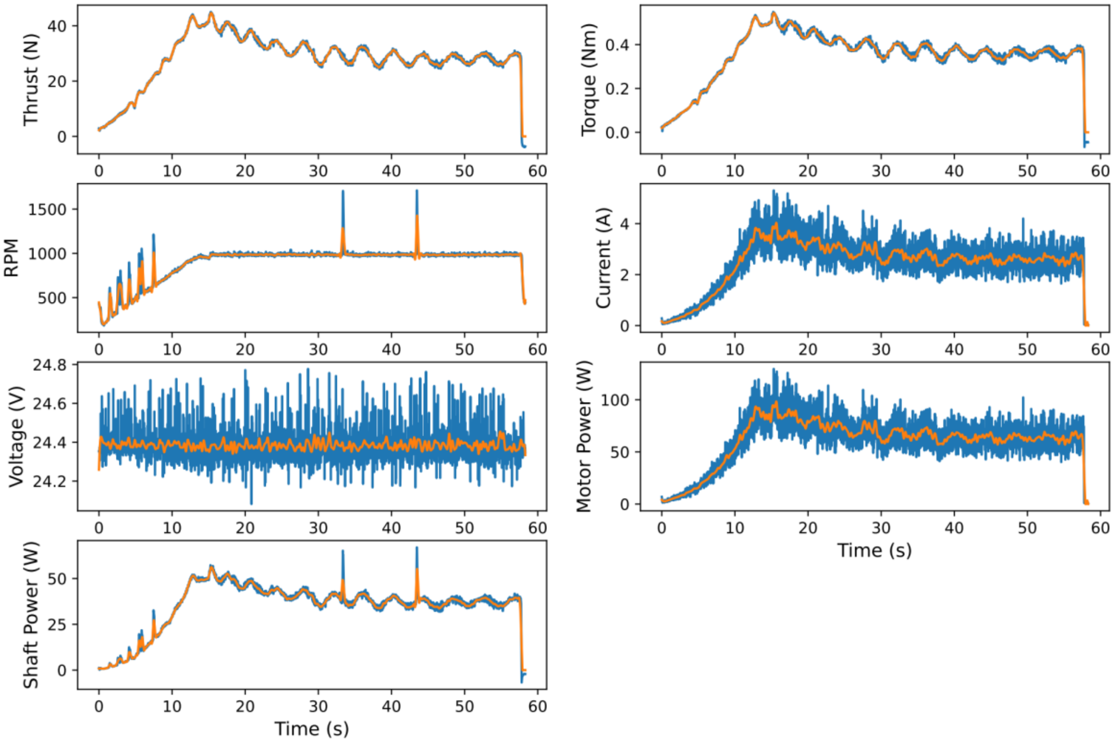
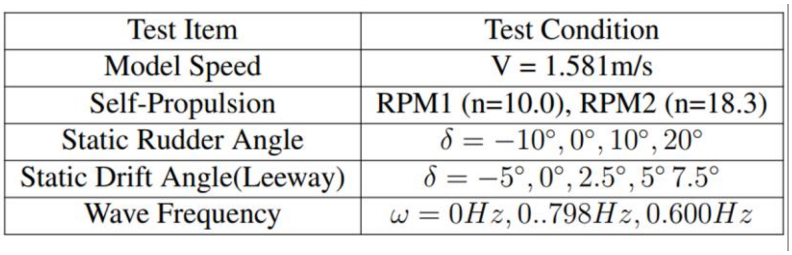


Figure 13 LASSO data showing how power variation changes with seastate for constant RPM: Run 54 irregular following sea

Influence of drift angle on rudder-propeller-interaction

As part of an MSc research project[5] a detailed study was carried out into the influence of waves on the powering performance of the KCS when towed at steady angle of drift. The range of parameters tested is given in Table 6. For these tests four rudder angles were tested per run. In these tests all three data acquisition systems were used. A similar richness of data, especially for the periodic performance in waves. This is well illustrated in Figure 14 which shows the fluctuation of wave height and propeller torque over a series of regular wave encounters. Figure 15 shows the periodic variation in model heave for different angles of drift with the model sitting deeper in the water at the higher drift angle but with similar amplitude for all drift angles tested. Finally derived Figure 16 shows the influence of drift and rudder angle on Hull side-force without propulsion and for two values of light and medium self-propulsion corresponding to conditions where a proportion of propulsive load is derived form wind forces rather than the propeller.

Table 6 KCS at drift in waves test matrix



Test Item	Test Condition
Model Speed	V = 1.581m/s
Self-Propulsion	RPM1 (n=10.0), RPM2 (n=18.3)
Static Rudder Angle	$\delta = -10^\circ, 0^\circ, 10^\circ, 20^\circ$
Static Drift Angle(Leeway)	$\delta = -5^\circ, 0^\circ, 2.5^\circ, 5^\circ\ 7.5^\circ$
Wave Frequency	$\omega = 0Hz, 0..798Hz, 0.600Hz$

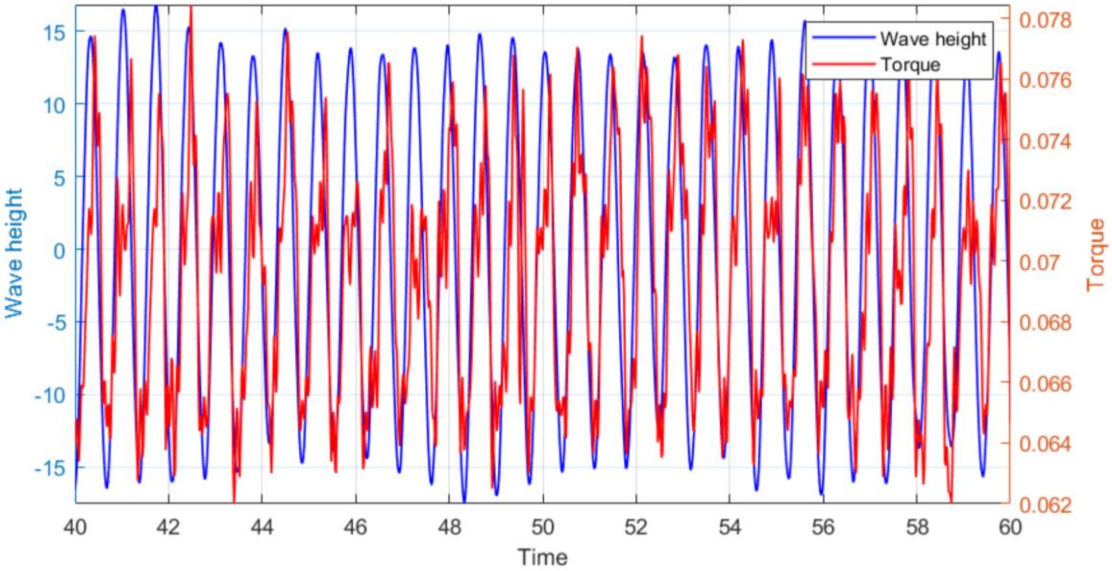
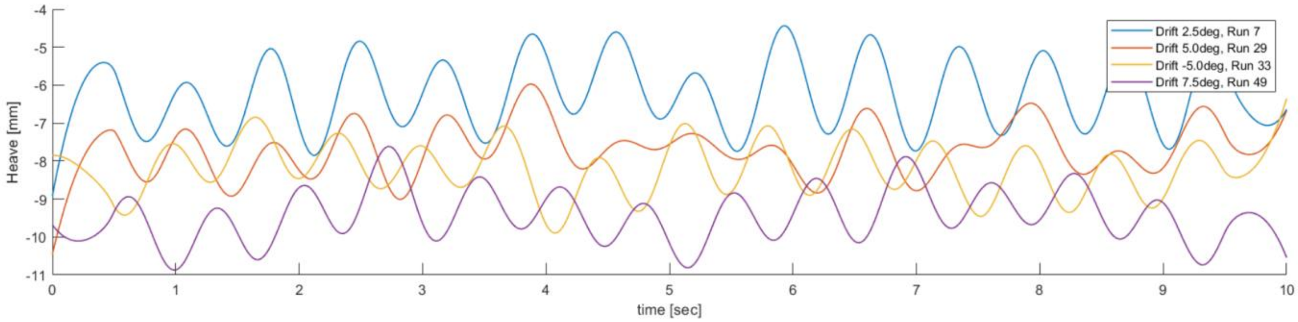
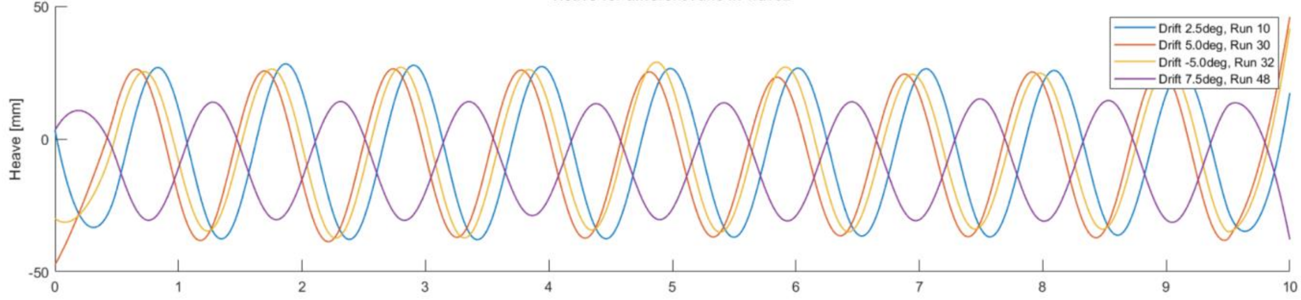


Figure 14 Comparison of propeller torque for June ’23 run 14 at constant rpm and regular head wave of 0.798 Hz



(a) Short wave – low amplitude wave



(b) Long wave – larger amplitude

Figure 15 Comparison of heave response for a constant rudder angle for two regular sea states and four drift angles

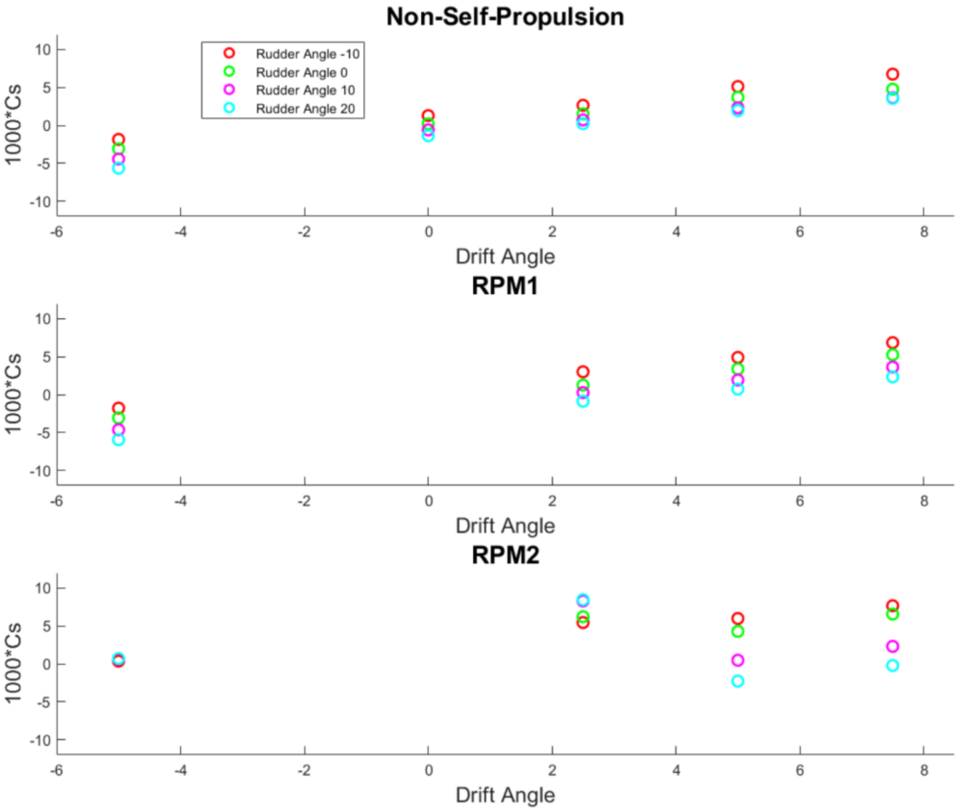


Figure 16 Non -dimensional hull side-force for drift angles between -5 and +7.5 deg and rudder angles between -10 and + 20 degrees for towed model free to heave and pitch

6. Conclusions

The use of an instrumented model significantly increases the understanding of the quality of resistance and powering data. However, it comes at a cost with the overall model costs increased by a factor of between 2 and 4 depending on the functionality required and for the model size tested. From an educational perspective this greater insight is of significant benefit deepening students understanding of how fundamental fluid dynamic behaviour controls ship powering. Such skills will be vital as the shipping sector needs seek out all possible methods of improving its energy efficiency from understanding how better to design hulls to operate at steady drift angles when fitted with wind assist systems or how the bow and stern arrangements can be optimised for operation in realistic sea states.

Interpreting the relationships between actual energy supplied through specific wave encounters will be important in understanding how energy saving devices will actually perform. This is true both at model scale and when comparing the measured performance on full scale ships where much richer date sets are available. The ability at model scale to instrument the power supplied to electric motors and measure all the power losses will give much greater appreciation of where energy losses are occurring. This deeper understanding should allow a more insightful approach to ship design that acknowledges that the addition of a simple power margin is not appropriate anymore.

The data will be vital for understanding how CFD can be used reliably as part of ship design for operational sea states[6] where measurement of force components for hull, propeller and rudder can be understood at model scale and scaling processes developed for predicting full scale performance.

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