The development of a 4IR 12m towing tank used for teaching and learning

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Abstract. This study investigates the design and development of a 12-meter towing tank designed for academic teaching and learning. The primary focus is on the experimental setup, the design and the testing of the system. The repeatability of the towing tank experiments was evaluated to ensure reliable results. A comparative analysis was conducted between the towing tank data and numerical simulations performed using MAXSURF Resistance software to validate the experimental outcomes.

1 Introduction

1.1 Background

Fig. 1. FORCE Technology towing tank [1].

Towing tanks play a vital role in the development and testing of ships within the naval architecture field. A typical towing tank experimental setup is shown in Figure 1. Towing tanks form a fundamental platform for the testing of new models and the development and optimization of maritime vessels[2].

The major benefit of towing tank testing is the prediction of the hydrodynamics of ship problems through experimental methods and testing [3]. The downside to towing tanks used in industry is the large space requirement and the significant budget required to have such a system. The use of such a system in the educational field will be largely beneficial for students to gain a complete understanding of how these systems are used to accurately predict how a vessel will behave prior to being built. Thus, the addition of a small-scale system would be beneficial to teaching and learning when incorporated with the naval architecture curriculum. Small-scale being under 20meters in length to allow for an affordable towing tank solution that various institutions can utilise in their curriculum.

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1.2 Related work

Towing tanks serve as controlled experimental facilities designed to evaluate a variety of parameters related to ship models [3]. These facilities allow for the prediction of key attributes, such as resistance, propulsion, and the manoeuvring of ships [1]. Benefits of these tests include accurate prediction of propulsive power, manoeuvrability, and resistance for a full-scale ship.
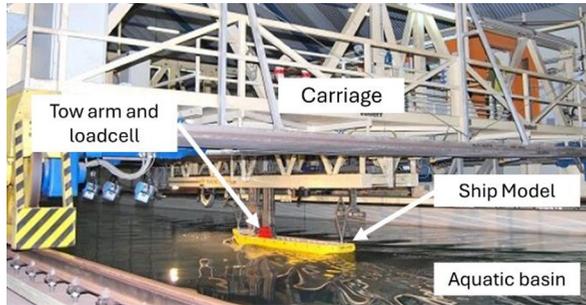

Fig. 2. Penerapan towing tank [4].

The basic configuration of a towing tank testing facility includes a confined aquatic basin, a carriage system equipped with various sensors, and a ship model pulled along the length of the tank. Figure 2 above illustrates the various components. Resistance and ship response to controlled conditions are the most common forms of data gathered from the tests [3].

Limited research has explored the use of small-scale towing tanks and their potential applications in industry, in this context small-scale is defined by towing tanks smaller than 20 meters in length. A study conducted by NTNU involved scaling a vessel of 36.25 meters in length to a 1:48 scale and performing tests in their 10.9-meter small-scale towing tank [5]. The results were then compared to data collected from scaling the same vessel to a 1:9 scale in SINTEF's flagship 260-meter towing tank facility [5].
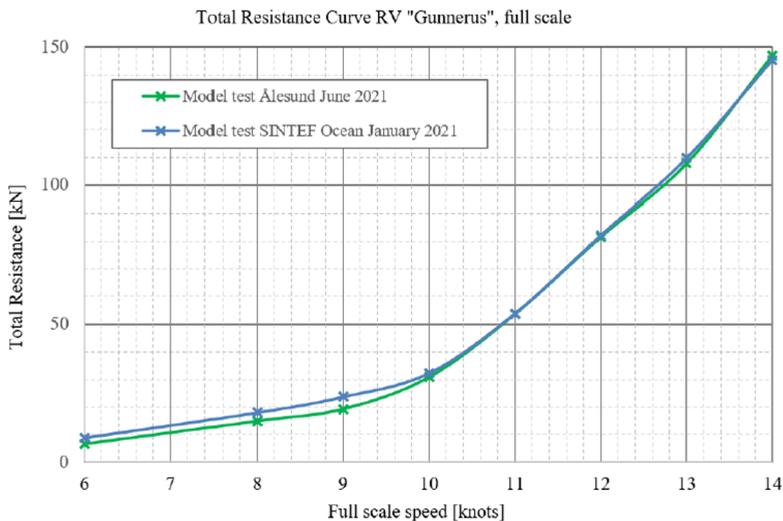

Fig. 3. NTNU results [5].

The results of the NTNU towing tank tests are shown in Figure 3. The data from NTNU demonstrate remarkable congruence with the SINTEF facility for a vessel speed starting at 10 knots. This is achieved despite NTNU having an actual tow length of only 8 meters. This study shows a promising ability for a small-scale towing tank to produce accurate data within an acceptable range for educational purposes. However, this study goes against ITTC regulations in terms of the ratio of model to tank length. According to ITTC, for a tank of 10.9 meters in length, the maximum model length should be 0.311 meters. The NTNU test used a 0.729-meter model. NTNU failed to abide by ITTC scaling guidelines but was still able to produce accurate results compare to those of SINTEF [5].

1.3 Codes and standards

The International Towing Tank Conference provides a set of codes and standards for towing tanks to ensure that experiments are carried out accurately. The ITTC provides a comprehensive set of guides and standards to perform accurate and reliable towing tank tests[6]. The set of rules allow for accurate scaling and model preparation. ITTC provides a guideline into the tank-to-model dimensions where a set of ratios are in place to ensure that the model does not exceed the recommended size for the towing tank, these are set to avoid interference between the model and the tank boundaries[6]. The ITTC fails to give a maximum scaling factor that should be used between the ship to model lengths.

According to ITTC 7.5-02-06-02 the tank is required to be 35 times the model's length, model length to tank width of 0.47 and a tank depth to model draft ratio of 4[6]. With tank dimensions of 12m in length, 1m in width and 0.62m in depth, a model can be up to 0.342m in length and have a draft of up to 0.155m. The ITTC fails to add a maximum beam (width) for the models.

1.4 Cost implications

Research related to the cost of building and running towing tank testing is limited. Sources such as DMS Marine Consulting predict towing tank resistance testing to cost approximately $20,000 USD ±50% [3]. As per A.H Day, the use of a large towing tank can cost many thousands of euros per day [7]. These costs apply for large towing tank testing used for ship design.

To compare to a smaller, similarly sized system, Omey Labs in the United Kingdom sells a wave tank for teaching institutions [8]. This company sells modular wave tank flumes with dimensions of 0.6 m x 0.6 m x 8.1 m in length for 20,000 pounds [8]. The only difference between these systems and the proposed 12-meter towing tank is the addition of a wave flap system. The 12-meter towing tank has tank dimensions of 1 m x 1 m x 12 m. The entire cost to manufacture this system and carriage is below R150,000 (approximately 6350 pounds and 8630 USD). Due to the size of the models being used, the test costs are significantly lower than those of large towing tank facilities.

1.5 Statistical analysis of data

ANOVA (Analysis of Variance) is a powerful method for conducting a Gage R&R (Repeatability and Reproducibility) study [9]. The ANOVA analysis provides the user with multiple outputs, such as the F-statistic value and the P-value.

The F-statistic value compares the variance within groups of data and determines whether the observed difference is real or due to chance; this determines whether the test is significant [10]. If the variance within groups is smaller than the variance between groups, the F test will yield a higher F-statistic value, which indicates that the observed difference is

likely real and not due to chance. In this context, to demonstrate the repeatability of the system, a low F-value would indicate smaller variation among groups and, therefore, a more repeatable system.

The null hypothesis of ANOVA assumes no difference among group means [10]. If any of the group means are significantly different from the overall mean, the null hypothesis is rejected [11]. The null hypothesis is evaluated based on the P-value from the experiment [10]. The alpha value is generally set at 0.05 for experiments, and any P-value above this supports the null hypothesis.

2 Experimental setup and design

This chapter presents the meticulous design of the towing tank facility, with an emphasis on the key engineering aspects considered. It describes the steps taken to design and build the 12-meter testing facility, including both the steel stand and the plexiglass tank. The design of the carriage and its associated components is also covered. The manufacturing of the model and carriage is explained.

2.1 Design criteria

The testing facility is limited to straight-line calm water resistance testing. The carriage is designed for speeds of up to 2 m/s. The carriage has a capability of 1.5 m/s² for both acceleration and deceleration stages. The working fluid of the tank is fresh water. The total resistance acting on the model and the travel speed at which the model and carriage are moving are recorded.

Due to space limitations at the research facility where the tank is built, the tank must not exceed 12 meters in length. The tank dimension is 12m in length,1m in width and 0.62m in depth, this is according to the space availability. In accordance with the ITTC codes and standards as mentioned in section 1.3, this system can facilitate of model 0.342m in length and 0.155m in draft. To ensure the system is comfortable to operate and view, the total height from the floor to the top of the plexiglass tank is 1.35m. This allows the user to be able to reach inside the tank to adjust the model whilst still ensuring that the model can be viewed by looking down into the tank and through the side panels.

The system needs to be able to measure the overall load acting on the tow arm of the carriage as this load is the total resistance acting on the boat model. In addition to load, the system needs to record the speed at which its travelling.

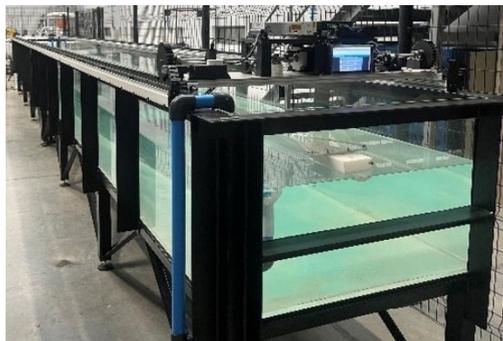### 2.2 Tank and stand design

Fig. 4. 12-meter tank assembly.

Figure 4 shows the final assembly of the towing tank, carriage, and model. The key aspects of the facility include the tank stand and acrylic tank design. The stand is designed to withstand the weight of the water and acrylic while ensuring structural stability. The acrylic tank is used to hold the water for the testing facility. This tank must be able to withstand the pressure exerted by the water on the walls of the tank.

For the assembly of the steel stand, mild steel is used. The steel includes 6 mm thick angle iron for the braces and top frame, 3 mm thick square and rectangular tubing for the legs and base of the frame, and lastly, 3 mm thick angle iron for the cross-bracing. The steel is coated with one layer of primer, followed by two layers of black paint.

A 10 mm thick sheet of HDPE plastic is placed between the base of the tank and the steel stand. This is used for cushioning and to add support to the base of the tank in the open area between the bottom braces of the steel stand. A 5 mm layer of SPX foam is then placed between the HDPE plastic and the base of the tank, as well as between the tank walls and the steel frame; this is used to cushion the tank against any potential sharp edges and misalignments.

The plumbing shown in Figure 4 is used for cleaning the tank water only.
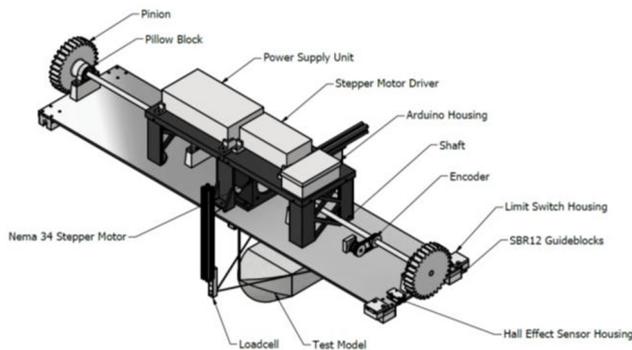
2.3 Carriage design

Fig. 5. Carriage assembly.

Figure 5 shows the carriage design. The carriage setup utilizes four SBR12 linear guide blocks. These guide blocks are positioned on each side of the carriage, one in each corner.

The system uses a NEMA 34 dual-shaft stepper motor connected via a shaft to the pinions. The motor is driven by the Wantai DQ860HA stepper driver, which incorporates 1/8 micro-stepping for smooth operation at high speeds. The shaft is supported and aligned using four pillow block bearing units. The rack used is the Centurion nylon rack. This rack is chosen for its corrosion resistance and strength. To achieve the correct torque and distance travelled per revolution, the pinion has a 120 mm pitch diameter. Due to availability and material requirements, a nylon 3D-printed pinion is used to ensure that both the rack and pinion are made of the same material. This, in turn, minimizes the resistance between the pinion and rack.
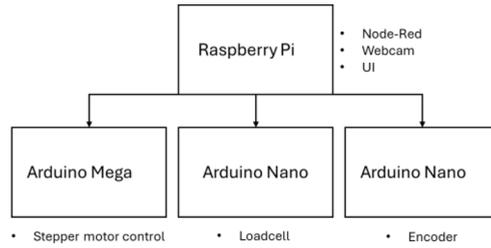
Fig. 6. Component hierarchy.

Figure 6, shown above, illustrates the component hierarchy of the electrical system. A Raspberry Pi and Node-RED are used for the user interface and to send commands to the various subsystems. This user interface and component arrangement contributes the 4IR status of the system by adding an advanced user interface using various microcontrollers and raspberry pi programming. An Arduino Mega is used with the AccelStepper Library to control the acceleration, deceleration, and test speed of the carriage by sending the required pulses to the stepper motor driver. The inputs for the stepper motor include test speed, acceleration rate, and deceleration rate.

An Arduino Nano is connected to the load cell and the Raspberry Pi. The load cell is calibrated using calibrated weights to produce a value rounded to one gram. The calibration process follows ITTC 7.6-01-01 [12]. The Arduino sends the value to the Raspberry Pi every 100 milliseconds.

A second Arduino Nano is used to send the speed of the carriage to the Raspberry Pi every 100 milliseconds. The speed is measured using an optical encoder with a resolution of 360 pulses per revolution.
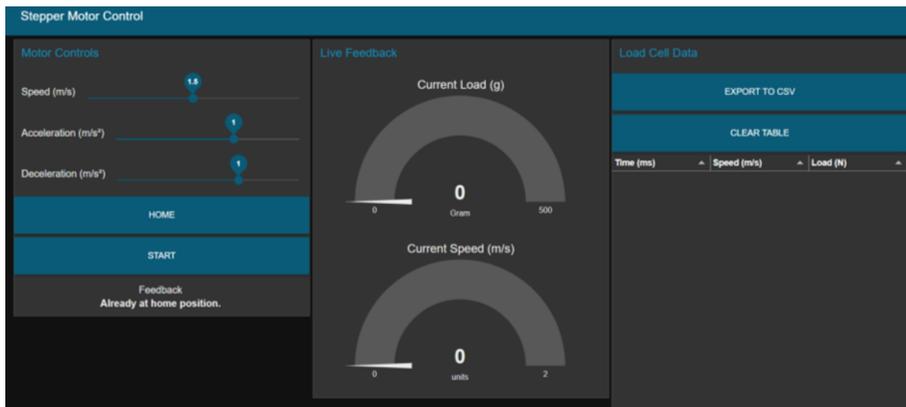

Fig. 7. User interface.

Figure 7 shows the user interface for the system. Under the motor controls column are the settings for test speed, acceleration, and deceleration. These are controlled using slider buttons in Node-RED. Additionally, there are two buttons. When the "HOME" button is pressed, the carriage moves at 0.2 m/s backward until the rear limit switch is triggered. The test will not start unless this step is completed. This ensures that the test only starts from the home position of the tank. The second button is the "START" button; when this is pressed, the starting sequence begins. Under the start button is a feedback window in which the Arduino Mega sends feedback when it has received various commands.

The live feedback column shows the live state of the load cell and the encoder. This aids the user in ensuring that when the model is stationary, the load cell is zeroed correctly.

The load cell data column has two buttons: "EXPORT TO CSV" and "CLEAR TABLE." The export to CSV button is used to download the table to the user's device as a CSV file, which can be imported into Excel. The clear table button is used to clear the table after the data has been exported. Under the clear table button is the table itself. It automatically plots when the start sequence commences and stops when the carriage is at rest.

The user interface, use of the Raspberry Pi, Arduino, and specified sensors, limit switches, and load cells are all used to develop the 4IR of the system. This is due to older towing tanks having very simplistic schematics with outdated user operating systems.

2.4 Maxsurf criteria

The Savitsky Pre-Planing method is used to calculate the resistance of a vessel in the region between displacement and planing conditions [13]. Hulls have three different modes when moving in water: displacement mode, semi-planing mode, and planing mode [14]. All hulls act as displacement hulls at lower speeds; however, not all hulls are designed for planing [14]. The Savitsky Pre-Planing method therefore covers the pre-planing region for planing vessels. The calculations for this method are based on J.A. Mercier & D. Savitsky [13].

The Savitsky Planing method is most accurate when the vessel is fully planing [13]. For the resistance calculations, all forces are assumed to pass through the centre of gravity of the vessel, and this is considered sufficiently accurate for the preliminary design stage [13]. The calculations for this method are based on D. Savitsky [13].

The Blount and Fox planing method modifies the Savitsky method to make it more suitable for true operational conditions; this includes corrections for test resistance to true operational resistance for bare hull forms and corrections for the influence of appendages [13].

The Lahtiharju method is used for estimating the resistance of planing hulls when planing is achieved [15].

The Wayman predictive method is originally used to predict engine power and therefore requires an efficiency dialog to be added to obtain accurate results [15].

The Holtrop algorithm is designed for predicting the resistance of tankers, general cargo ships, fishing vessels, tugs, container ships, and frigates [15].

Crompton's method is an algorithm designed for resistance prediction of typical patrol, training, or recreational powerboat-type hull forms with transom sterns operating in the displacement and semi-displacement regions [15].

Fung's method is an algorithm applicable for resistance prediction of displacement ships with transom stern hulls, generally for larger vessels than those covered by Crompton's method [15]. This method was originally developed using regression based on 739 models at the David Taylor Model Basin [15].

The Van Oortmerssen method is useful for estimating resistance for smaller vessels, such as trawlers and tugs [15].

Series 60 is for resistance prediction of single-screw cargo ships [15].

The KR Barge prediction method is suitable for box-shaped vessels, such as barges, operating in displacement mode [15].

2.5 Model manufacturing

A 3D printed model is used in the towing tank to test the repeatability of the facility and the accuracy when compared to a Maxsurf generated resistance curve. 3D printing is an accurate method to manufacture the models with small surfaces and curves.

Table 1. Model specifications.

Parameter	Mono hull Model
Length overall (LOA) [m]	0.3
Length of waterline (LWL) [m]	0.265
Beam at waterline (B) [m]	0.114
Draft (T) [m]	0.03
Weight Displacement (∇) [kg]	0.506
Centre of buoyancy from transom [m]	0.105

Table 1 illustrates the monohull model specifications. The model is designed in MAXSURF Modeler and exported to a Rhino 3DM file. This 3DM file is then imported into Inventor software, where it can be exported as an STL file. This is done because there is no direct way to export a MAXSURF model to an STL file. The STL file is then imported into Creality Print, where it is printed using PLA on a Creality K1 Max printer. A model of 0.3 m in length is used, as the build plate for the Creality K1 Max is 0.3 m x 0.3 m x 0.3 m. A scale factor of 99.9% is applied to the model to ensure that it has the correct dimensions after two layers of epoxy resin have been applied.
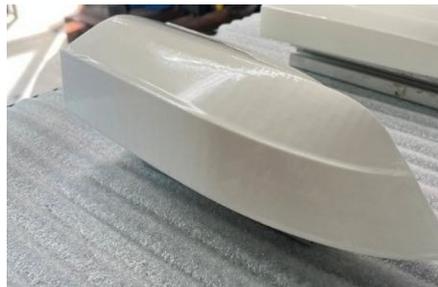

Fig. 8. Monohull model.

Figure 8 shows the monohull model after two layers of epoxy resin has been layered on the model. The epoxy is used to seal any potential gaps between the layers that occurred during the printing process. Lead discs are used to ballast the model to get the correct draft and pitch.

3 Research methodology

3.1 Structural analysis

An FEA needed to be performed to determine the structural stability of the steel stand and acrylic tank. This includes a static test using a variable load acting on the inside of the tank. This variable load is due to the water pressure changing with depth. This FEA was done in SolidWorks.

An FMEA was conducted to highlight any possible risks associated with the towing tank. This was considered in the design to ensure that any potential risks were accounted for and mitigated.

3.2 Repeatability

To evaluate the system's repeatability and determine whether the system can produce reliable and consistent results, a series of tests need to be conducted at various speed intervals. These include speeds of 0.5 m/s, 1 m/s, 1.5 m/s, and 2 m/s. Three tests were conducted at each speed using identical test settings. A period of 15 minutes was required to ensure that the water has sufficient time to settle between test runs.

A single-factor ANOVA analysis was performed between the three different test runs to ensure that each test speed is reliable, not due to chance, and supports the null hypothesis.

3.3 Comparison with software results

A choice was made to compare the results of the towing tank with MAXSURF resistance software. This was because MAXSURF is regularly used in the naval architecture curriculum, and it would be beneficial for the university to have this comparison for students to refer to when conducting practical experiments in the towing tank.

To accurately compare the results, the model was manufactured according to the MAXSURF Modeler design. This ensured that there was an identical digital twin of the model. A series of resistance tests were conducted at various speeds and then compared to the MAXSURF-generated results. This was done while ensuring the water temperature remains within 0.5 degrees from the start to the finish of the experiment [16].

4 Results and discussion

This section presents the Finite Element Analysis (FEA) results of the static 12-meter steel stand and acrylic tank. The structural simulation of the tank and stand is conducted prior to manufacturing to ensure the tank can withstand the pressure and the stand can support the weight.

This section will also include preliminary tests of a 300mm monohull model that determined the repeatability of the system and its accuracy, when compared to software-generated results.
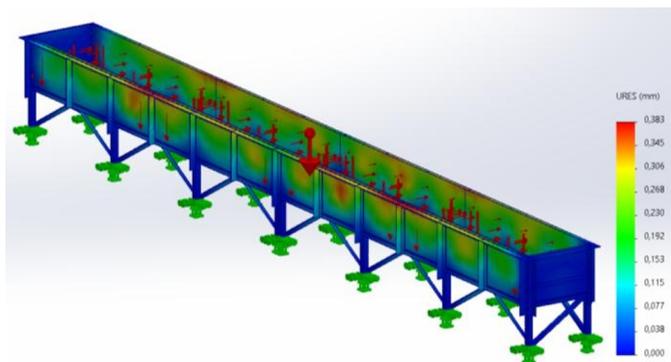
4.1 Finite element analysis

Fig. 9. 12-meter tank displacement graph.

An FEA has been conducted to assess the tank's displacement and its structural integrity. This was achieved by applying a non-uniform load to simulate the hydrostatic force within the tank. This simulated both the pressure on the side panels of the tank and the downward force acting on the frame. Initial tests were conducted with fewer vertical support struts. These tests included support struts at each leg but not at the centre between legs. The results showed significant displacement, which led to the addition of struts positioned between the legs.

As illustrated in Figure 9, the pressure acts on all the walls of the tank, and the feet are set to a fixed position. The results from the FEA showed minimal displacement, with a maximum of 0.383 mm.
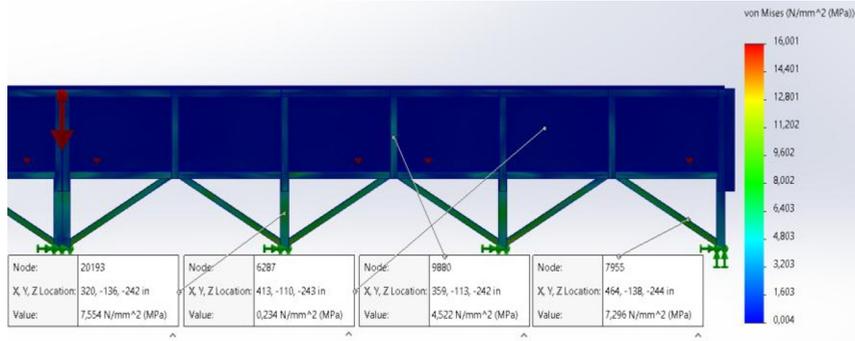

Fig. 10. Stress profile for the 12-meter tank.

The stress profile for the tank and stand is shown in Figure 10. The stress shown on both the tank and steel stand was minor and well below the yield stress of the material. The yield strength of cast acrylic is a 110 MPA[17]. Therefore, the stress acting on the acrylic was well within its yield strength. With the maximum stress of 16Mpa, the system is overdesigned and excessively strong.

The system could be made cheaper by using thinner steel. However, having the system overdesigned will benefit any further additions to the tank such as a wave simulator, which would exert a larger force on the acrylic and steel stand.

Table 2. Failure mode and effects analysis.

Failure mode and effects analysis				
Calculation of Risk Preference Number [RPN]				
Failure Mode	Severity [1-lowest, 10 highest]	Probability of occurrence [1-lowest, 10 highest]	Probability of detection [1-lowest, 10 highest]	RPN
Seal leaks due to water pressure	5	4	9	180
Cracking due to carriage malfunction	7	4	10	280
Welds fail due to corrosion	6	3	7	126

The design of the towing tank showed minimal potential failures. These failures included seal leaks, acrylic cracks, and weld corrosion, each of which can be addressed and repaired with ease.

The critical concern highlighted by the FMEA in Table 2 is cracking due to carriage malfunction. This can occur when the high-speed carriage fails to slow down due to either a motor or sensor failure. This failure had the highest RPN and therefore is a priority to address.
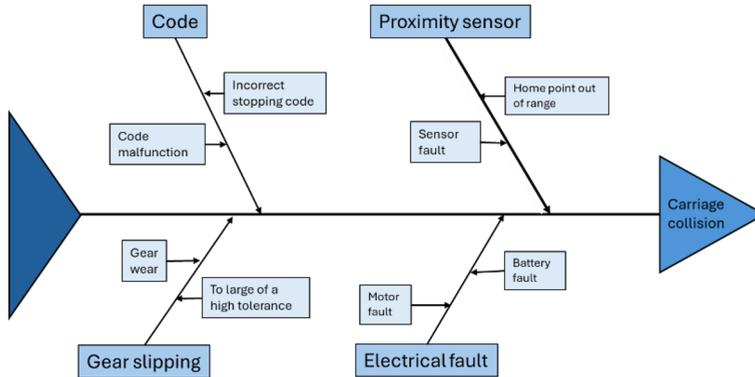

Fig. 11. Fish bone diagram.

Figure 11 represents the potential causes of a carriage collision. Each cause is then broken down further to show the root of the problem.
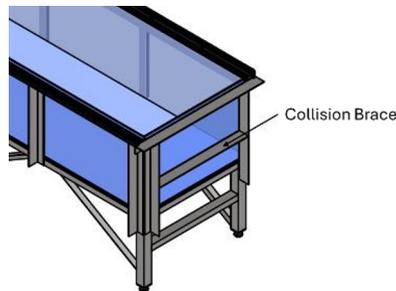

Fig. 12. End brace.

According to the fishbone diagram in Figure 11 and the FMEA in Table 2, the predominant risk to the tank's integrity was the potential collision between the model and the tank wall. A horizontal brace has been placed at the end of the tank. This brace is made from 90 x 65 x 6 mm angle iron, as shown in Figure 12. It braces the tank against water pressure and provides additional support in the collision area if a collision occurs between the model and the end of the tank. Other preventive actions included removing the last section of the rack, which stops the motor from pushing the carriage past the final stop point. The front limit switch on the carriage will cause the motor to stop immediately if activated. Tape is also placed on the SBR 12 guide rail at the end to cause the bearing blocks to jam if they reach this area.

4.2 Repeatability of the system

According to ITTC-7.5-02-02-02 [16], the water temperature should vary by less than ±0.5°C during the test period, as this corresponds to a water density change of ±0.01%. Therefore,

during the test period, the water temperature was monitored to ensure it did not change by more than 0.5°C.

Table 3. Repeatability analysis.

Speed (m/s)	F value	P value
0.5	0.17793	0.83709
1	1.31036	0.27132
1.5	0.35877	0.69902
2	3.14075	0.04701

The ANOVA single-factor analysis results are shown in Table 3. The alpha value is set to 0.05. For the null hypothesis to be supported, the p-value must therefore be larger than 0.05. The results showed that all tests, except for the 2 m/s test, supported the null hypothesis, indicating that the results were not due to chance.

The F-value indicates the likelihood that the data set is reliable and not due to chance; the lower this value, the less likely it is that the results are due to chance. It was observed that tests at 0.5 m/s to 1.5 m/s performed best based on the highest p-values, and tests at 0.5 m/s and 1.5 m/s performed best according to the F-value.

4.3 Experimental test compared to Maxsurf

Maxsurf is a naval architecture software used for designing marine vessels, including hull modelling, stability, motion and resistance prediction, structural analysis, and the export of vessel detailing. The Maxsurf Modeler is used to create a standard 300mm monohull model for initial towing tank testing.

Maxsurf Resistance software is used to predict the resistance acting on the model. The resistance software includes several formulas for resistance prediction. For planing testing, it offers the Savitsky Pre-Planing, Savitsky Planing, Blount and Fox, Lahtiharju, and Wyman resistance methods. For displacement testing, it includes the Holtrop, Compton, Fung, van Oortmerssen, Series 60, and KR Barge resistance methods.

Table 4. Maxsurf resistance.

Speed (m/s)	Planing				Displacement			
	Savitsky Pre-Planing (N)	Savitsky Planing (N)	Blount and Fox (N)	Lahtiharju (N)	Holtrop (N)	Van oortmerssen (N)	Compton (N)	Fung (N)
0,5	-	-	-	-	0,08	0,07	0,1	0,06
0,7	-	-	-	-	0,17	0,19	0,3	0,11
0,9	0,64	-	0,52	-	0,36	0,44	0,73	0,25
1,1	1,02	0,98	0,98	-	0,54	0,4	-	0,51
1,3	1,03	1,09	1,23	-	0,65	0,4	-	0,67
1,5	1,07	1,15	1,3	0,67	0,76	0,46	-	0,78

| 1,7 | 1,13 | 1,15 | 1,27 | 0,85 | 0,91 | 0,56 | - | 0,89 |
| 1,9 | - | 1,13 | 1,22 | 1,13 | 1,08 | 0,68 | - | 1,01 |

Table 4, shown above, presents the Maxsurf-generated results based on the monohull model. The results included both planing and displacement formulas. The Wyman, Series 60, and KR Barge methods were excluded because they are limited to specific hull shapes.

It is noted that the monohull model was a planing hull; however, at lower speeds, it acts as a displacement hull. Therefore, displacement methods are also included for lower model speeds.

Table 5. Result difference.

		Planing				Displacement			
Speed (M/S)	Test Data (N)	Savitsky Pre-Planing %	Savitsky Planing %	Blount and Fox %	Lahtiharj u %	Holtrop %	Van oortmers sen %	Compton %	Fung %
0,5	0,065	-	-	-	-	18,33	6,66	34,67	-8,89
0,7	0,208	-	-	-	-	-22,48	-9,59	30,60	-89,28
0,9	0,673	-5,11	-	-29,37	-	-86,87	-52,89	7,85	-169,09
1,1	1,022	-0,15	-4,24	-4,24	-	-89,17	-155,38	-	-100,30
1,3	1,034	-0,41	5,12	15,92	-	-59,11	-158,55	-	-54,36
1,5	1,156	-8,04	-0,53	11,07	-72,55	-52,11	-151,32	-	-48,21
1,7	1,332	-17,87	-15,82	-4,87	-56,70	-46,36	-137,84	-	-49,65
1,9	1,303	-	-15,35	-6,84	-15,35	-20,69	-91,69	-	-29,06

Table 5 shows the percentage difference between the data gathered during testing and the data generated by Maxsurf Resistance. The values presented under the planing and displacement columns represent the percentage difference between the test data and the Maxsurf-generated data. The test data was collected by running the model at a set speed and calculating the average of the resistance values at constant speed. Outliers have not been filtered out for this dataset.

The negative percentage difference shows that the test data value is larger than the software generated data. The positive percentage will show that the software generated value is larger than the test data value.

The comparison showed that at lower speeds, such as 0.5 m/s and 0.7 m/s, van Oortmerssen's approach performs the best. From speeds of 0.9 m/s to 1.3 m/s, Savitsky Pre-Planing performs the best. From 1.5 m/s onward, Blount and Fox and Savitsky Planing perform the best.

These results were expected, as the model acts as a displacement hull, then a pre-planing hull, and finally a planing hull. Referring to subsection 2.4, we can see that these results align with the derivation of each method.
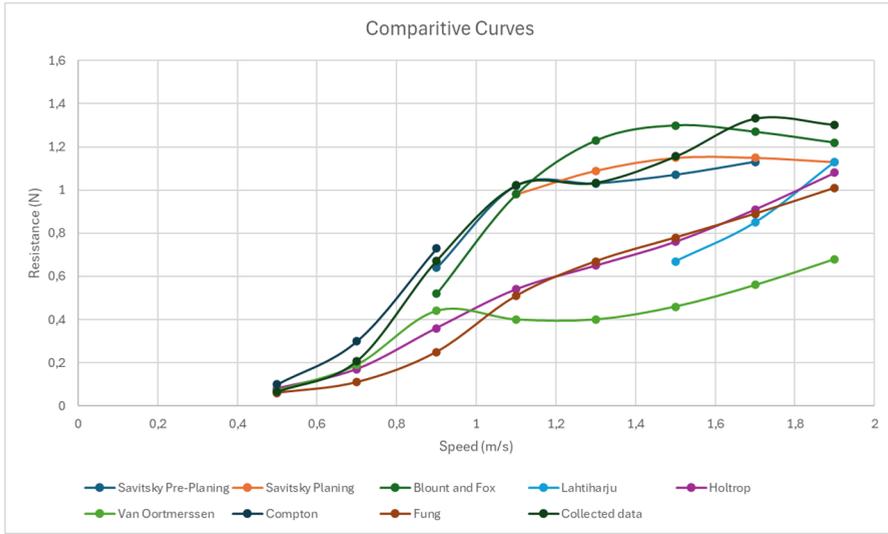
Fig. 13. Resistance curves.

Figure 13 shows the different resistance curves based on the Maxsurf simulation and test experiment. The model experiences a minor increase in resistance from 1.1 m/s to 1.3 m/s, which could indicate the initial stages of planing for the monohull. At 1.7 m/s, the model experiences its maximum resistance of 1.33 N, which is slightly higher than the 1.3 N experienced at 1.9 m/s. Further testing is required to determine at which speed the model is fully planing.

Figure 13 shows how the various formulas are only applicable to certain speeds based on the vessel condition. The curves accurately show which formulas are most applicable to each test speed of the specific model.

4 Conclusion

This research paves the way for the future development of small-scale towing tanks. The benefits of such systems will be seen across the tertiary education sector as well as in industry. This test platform serves to enhance the current curriculum and enhance the naval architecture syllabus.

Although ongoing, this research has laid the foundation for the development of such a system and its major benefits in both industry and academic environments. The results from Section 4.1 show that key aspects of the design, including the steel structure and the plexiglass tank, have been considered, and a final design has been chosen and manufactured. The structural stability of the facility has been analysed to ensure it is structurally sound and can safely withstand the weight and pressure of the water. The system showed to be overdesigned and have minor displacement and stress. This is a positive factor as it allows for future additions to the tank such as a wave flat system. The overdesigned acrylic and steel will allow for the larger stress and pressure exerted by the waves and wave making equipment.

The results in Section 4.2 illustrate the system's ability to accurately repeat tests at various speeds and highlight the need for minor improvements to ensure all test speeds are repeatable. The comparison between Maxsurf and the test data provided key insights into which methods best suit the model at various speeds. The results of the towing tank can therefore be accurately compared to Maxsurf-generated values.

Future work on the tank and experimental system includes more in-depth testing of various models at different speeds. An investigation comparing this system to a larger towing tank would be beneficial in proving this system's ability to produce accurate and reliable results. Modifications to the system could include a wave flap system to generate known waveforms to assess a model's stability against a known wave.

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