Investigation of the influence of tank geometry on a vessel’s stability under free surface effect when in coastal waters

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Abstract. Tank sizes on liquid cargo carriers are becoming larger to minimise wasted spaces on-board and maximise payload capacity. This trend can significantly affect a vessel’s stability and its design. Therefore, this paper investigates whether spherical tanks provide better stability than a traditional tank formed with vertical sides under a range of free surface scenarios. The motions of a model liquid cargo carrier hull with various sizes of tanks and various fill levels has been investigated in a coastal basin. Regular waves of various heights and frequencies have been generated and the rolling motions of the hull have been documented. Results have shown that spherical tanks offer less free surface effects compared to vertical sided tanks thus create less rolling motion. In contrast, when the hull has four tanks, all of those with free surfaces, the vertical sided tanks provide better stability up to 50% fill levels whereas spherical tanks induce less roll between the fill levels 50% and 100%.

1. Introduction

With increasing demand for liquid cargo to be transported [1], there is a growing interest in using unbaﬄed tanks, instead of baﬄed tanks to maximise cargo carrying capacity [2]. It is of importance to maximise space to maximise proﬁt while not putting the safety of the vessel at risk. This highlights a gap in research regarding direct comparisons among various tank designs. Typically, vertical sided tanks are used in crude oil tankers for cargo storage [3]. Cruise ships also utilise those tanks for potable water storage. However, spherical tanks are utilised on some LNG vessels [4] [5]. This design is favourable mainly due to the pressure that the LNG is stored under [6]. However, spherical and vertical sided, both types of tanks typically have large volume of liquids with varying free surfaces.

A vessel with partially ﬁlled tank(s) and exposed to external forces (e.g. wind and waves) results in sloshing within the tank(s). Sloshing is a nonlinear movement of liquids inside tanks that are not full or completely empty [7]. Liquid movement creates dynamic loads on the tank that are transmitted into the vessel [8]. Besides the impact forces on the tank walls, sloshing may also have an effect on the vessel’s motions [9].

No known research has previously compared between spherical and vertical sided tank designs. Therefore, this paper looks to identify and compare the differences when the tanks have free surfaces and are subjected to wave loads. This paper compares vertical sided tanks to spherical tanks with a range of free surfaces through a study conducted using a model liquid cargo carrier hull within a coastal basin at the University of Plymouth, UK.
The aim of this paper is to identify how both tank designs affect a liquid cargo carrier’s roll motions when the vessel experiences wave loads in coastal waters. The aims have been achieved through direct comparison between the two tank designs and identifying how increasing levels of fluid within the tanks affects the vessel’s stability. The effects of wave heights and frequencies have also been investigated to identify the effect this has on the vessel as a comparison between the two tank designs.

2. Methodology

It is common to use a wave machine and/or towing tank for vessel testing [10]. In recent years, computer software has become more capable of doing this [11]. However, using a combination of physical and computer modelling is more efficient, as physical modelling is more expensive but allows confirmation that computer-based results are accurate.

To achieve the aims of the project, model spherical tanks were manufactured in-house using laboratory facilities as shown in figure 1 whereas off the shelf food containers (shown in figure 2) were used as model vertical sided tanks. The experiment was conducted using the University of Plymouth’s coastal basin and model hull was utilised and the vertical sided tanks were installed, shown in figure 4.

The model hull used for this experiment has a depth of 20cm. LNG vessels typically have a depth of 26 metres, therefore, it would be feasible to consider an LNG vessel with a depth of 20 metres for the purpose of this experiment [10]. This then allows a scale of 1cm:1m to be used. The size of the hull allowed for four tanks to be installed upon it. Using steady wind at a speed of 30 knots over 24 hours with a fetch of 340 miles, this would equate to an end average wave height of 3 metres and a significant wave height of 5 metres [12]. This has allowed for a sensible model wave height of 2- and 3-metre waves to be used in the basin.

![Figure 1](image1.png)  **Figure 1.** Manufactured sphere tanks left on their supports. Behind the spheres is the model vessel.

![Figure 2](image2.png)  **Figure 2.** Off the shelf food container used as model vertical sided tank.

2.1. Tank manufacturing

The spheres used in the experiments were manufactured by hand laminate with weaved glass fibre and epoxy resin. First, pre-inflated soccer balls of 23 cm diameter were wrapped with glass fibre fabrics prior to apply the resin. A coat of yacht varnish was also applied to ensure the spheres were watertight. The capacity of the spheres slightly varied between each sphere. This is believed to have been the result of the balls being pre-inflated with air and thus the exact dimension would vary.

2.2. Experimental set up

The centre of gravity (CoG) was calculated for the spheres and the vertical sided tanks. The vertical sided tanks were raised from the hull bottom to keep the CoG of the tanks (when at maximum capacity) at the same height as that of the spherical tanks.

The hull has been fitted with four tanks, that have been assigned a tank number running from the bow of the vessel to the stern, starting with the most forward tank being “Tank 1”. The spherical tanks have the following capacities; tank 1 – 5.0 litres, tank 2 – 5.2 litres, tank 3 – 5.1 litres and tank 4 – 4.7
litres. Fill levels for each sphere were adjusted accordingly, while vertical sided tanks, made from food containers, were purchased with a total capacity for each tank as 5.2 litres. The minor discrepancies in size (up to 0.5 litres) would only have a minor impact, which can be addressed through discounting anomalies.

The hull was tested under two different conditions, one with vertical sided tanks installed and another with spherical tanks installed. Initial controls were taken with empty tanks installed on the hull. These were then exposed to wave heights of 2 or 3 cm and at a frequency of 0.75 Hz or 0.63 Hz.

Tests were conducted for 2 minutes and each test was repeated 3 times with a 2-minute interval to allow time for the water to settle. A six degrees of freedom motion sensor (6DOF) was installed at the hull’s CoG. The 6DOF is an analogue sensor that includes outputs of three gyroscope/rate sensors and three DC accelerometers. The 6DOF recorded hull motions, with the X axis has been assigned to the direction of the waves, Y axis longitudinally to the waves and Z vertically. The 6DOF is calibrated at +24 °C at 10 Vdc. The sensitivity is in 20 mV and has an accuracy of ±15%.

The volume of liquid within tanks was increased by 10% per test up to the maximum volume or until the vessel became too unstable and risked damaging the 6DOF. Results generated from the 6DOF have been recorded in radians and then organised highest to lowest. The highest and the lowest 1% has been averaged as results have been taken at set timed intervals. There is also a discrepancy within the wave height of ±1 cm.

2.3. Coastal basin set up
Distance of the hull from the wave generation paddles was 583 cm. Three wave gauges were used to determine the height of the wave (see figures 3 & 4).
- Wave gauge 1 was located 222 cm from the hull in the direction of the travel of the wave.
- Wave gauge 2 was located 100 cm in the direction of the travel of the wave.
- Wave gauge 3 was located 98 cm beyond the hull away from the direction of travel of the wave.
- The beach started 251 cm from the port side of the vessel.
- The water line ended 910 cm from the port side of the vessel.

To improve data accuracy, before testing commenced each day, the three wave gauges were calibrated. The coastal basin was set to a water depth of 500 mm, the maximum daily variation to this was ±10 mm. This change in level will have had an impact upon the waves generated. However, this was minimised by topping the basin up with water daily to achieve the correct working level.

The wave gauges are calibrated using the manufactures supplied computer program, this involved setting the correct basin working water level of 500 mm. The wave gauges where raised 10 cm, from there working level and the water allowed to settle before calibrating. The gauges where then lowered 10 cm, from there working level and the water allowed to settle, then calibrated. Lastly, the gauges were set to the working level and calibrated. The program uses the current flow across the sensors at each depth to calculate the changes in water level.

**Figure 3.** The hull’s setup within the coastal basin showing the wave generation paddles along with the supporting structure holding the vessel in position. The wave gauges are fixed to the supporting structure.
3. Results
Upon completion of testing, the generated data has been imputed to Microsoft Excel and MATLAB to generate workable data to compare between different run settings. All test setups were repeated three times to improve the accuracy of the data and allow for anomalies within the results to be identified. The results from all three runs have been averaged using the maximum 1% of roll data generated.

3.1. Wave data
All wave height data utilised has been inputted into MATLAB software and de-noised to develop readable and accurate sinusoidal wave graphs. This software also has developed the maximum and the minimum heights of the waves. A sample of wave data primarily from wave gauge 1 (figure 5) has been taken to appraise how the waves formed compared to desired wave height and thus how this could have affected the data generated.

![Wave Data Graph](image_url)

**Figure 5.** Waves generated with a wave set height of 0.02 m and frequency of 0.75 Hz. Data points taken from wave gauge 1.

It has been observed that there was a variation between the set wave height and the wave height generated. This has resulted in some deviation within the results, however, as an average of maximum 1% of roll was taken this has minimised discrepancies within varying wave heights. This also gives results closer to what would be expected within a real-world scenario as natural waves will have variable heights. It has been observed that some wave gauges appeared to have failed to calibrate correctly in some of the data. The wave gauge results have been compared with the other two gauges to determine the actual height of waves and thus the defective wave gauge has been discounted from the results.
3.2. Hull stability

The hull’s stability has been compared among three variables: wave height, frequency and the tank shape. From the results, it is surprising to see that the hull becomes slightly more stable when it had a low percentage of water in the tanks. It was expected that the roll angle would increase when the free surface was increased. This is likely due to the CoG of the vessel becoming lower.

The wave data has shown that there is some variation between the wave set height and the wave height achieved. This has varied slightly between run to run of the same setting. The results shown within the following figures have been calculated using the highest or the lowest one percent depending on the direction of roll. This equates to around 157 results per direction of roll. All figures within the “hull stability” show the hull’s roll angle in radians and when the hull was side-on to the waves.

Tests were repeated by increasing the fill levels of all the tanks by 10% for each test setup, wave height and frequency. Once all variations were conducted for one tank design, the tanks were changed, and the same tests conducted on the hull with the other tank design. These was repeated until the hull became too unstable and risked damaging the 6DOF sensor located in the hull.

3.2.1. A wave height of 0.03 m and at a frequency of 0.63 Hz

Figure 6 shows the average results for a wave height of 0.03 m and at a frequency of 0.63 Hz. It is to be noted that the vertical sided tanks resulted in less roll between 10% and 60% fill levels than that of the spherical tanks. Greater than 60% fill level, the spherical tanks impact upon the hull’s stability is less than that of the vertical sided tanks.

The roll increases quicker after 60% of fill level as seen in figure 6. It is to be noted however, that although the roll of the hull with spherical tanks increases, the roll angle is lower than that of the vertical sided tanks. It has also been observed that the hull when fitted with spherical tanks was able to hold a greater volume of water before becoming too unstable to continue testing.

Fascinatingly at 30% fill level, the vertical sided tanks only induce a roll of 0.408 radians whereas spherical tanks have an average roll angle of 0.461 radians. At 70% fill level, the vertical sided tanks induce a roll of 0.881 radians whereas the hull with spherical tanks had a roll of 0.645 radians.

![Figure 6](image)

**Figure 6.** Comparison between vertical sided tanks and spherical tanks with a wave height of 0.03 m and at a frequency of 0.63 Hz.

3.2.2. A wave height of 0.02m and at a frequency of 0.75 Hz

Figure 7 shows all tanks filled with varying percentage of water with a wave height of 0.02m and at a frequency of 0.75 Hz. It was noted that in this set up, the hull handled in a similar manner to when the
wave height was 0.03 m and at a frequency of 0.63 Hz. However, the hull became unstable at 70% fill level for both types of tanks.

The hull has greater roll from the spherical tanks between 20% to 50% fill levels. However, past 50% fill level, the spherical tanks become more stable. It can be said that at 40% fill level, the spherical tanks have an average roll of 0.51 radians whereas the vertical sided tanks’ average roll is only 0.44 radians, a difference of 15%, when at a wave height of 0.02 m and wave frequency of 0.75 Hz.

In contrast, when the tanks were at 70% fill level, the roll with spherical tanks was only 1.08 radians whereas the vertical sided tanks achieved an average roll of 1.3 radians, a difference of 20%. It is expected that this trend would have continued if it had been possible to test to 100% capacity. Both tank designs would have increased the roll of the hull whereas it is predicted that the roll from the spherical tanks would have been less than that experienced by the vertical sided tanks.

![Vessel Roll Comparison](image)

**Figure 7.** Comparison between vertical sided tanks and spherical tanks with a wave height of 0.02 m and at a frequency of 0.75 Hz.

3.2.3. Only filling one tank identified as tank two

Figure 8 compares vertical sided tanks with a wave height of 0.02 m and frequency of 0.75 Hz against the same wave height and at a frequency of 0.63 Hz. Figure 9 shows the same set up, however using the spherical tanks. This has shown that changing just the frequency of the waves has a direct impact upon a hull’s stability. It is noted in both figures 8 and 9 that the hull handles comparatively the same rolling motion. Although the roll angle has increased by a factor of approximately 1.5 when the wave frequency is increased from 0.65 Hz to 0.75 Hz.

Although the angle increased, both followed the same pattern. As can be seen with the spherical tank between 10% and 50% fill levels in figure 9, the stability of the hull is improved. Whereas for the vertical sided tanks, the stability did not improve once the fill levels were increased, it stayed at a constant stability between 10% and 60% fill levels as seen in figure 8.

Surprisingly, the vertical sided tank shows a similar trend to that of the spherical tanks up to 80% fill level. After this, it is seen that the hull’s roll increases. The increase in roll for the vertical sided tank is probably because the top of the container was much higher in the hull compared to that of the sphere. Just using spherical tank 2, it has been observed in both frequency settings to have altered the roll of the hull less than that of the vertical sided tanks.
The roll angle when at 0.63 Hz wave frequency and 100% full is on average 0.3139 radians. Whereas at 10% fill level, the average roll is 0.2919 radians. In contrast, for the vertical sided tank at 100% fill level, the roll has increased to 0.3765 radians. This highlights the effect of the higher mass within the hull. At 10% fill level, the vertical sided tank has a similar roll angle of 0.2993 radians. The negative roll recorded shows that the hull in both directions experienced the same motion behaviour.

**Figure 8.** Vertical sided tank 2 only being filled at varying percentages showing a comparison of waves at 0.02 m and a frequency of 0.75 Hz or 0.63 Hz.

**Figure 9.** Spherical tank 2 filled at varying percentages showing a comparison of waves at 0.02 m and a frequency of 0.75 Hz or 0.63 Hz.

4. Conclusion
It is seen in all scenarios tested that vertical sided tanks with increasing percentage of liquid above 50% fill levels have an increased impact upon the vessel. Otherwise, the vertical sided tanks had less of an impact upon the vessel’s stability. Above 50% fill levels, the vessel’s roll increases for the
vertical sided tanks whereas it stabilises for the spherical tanks. Although both tanks have the same CoG, there is more mass higher in the vessel in the vertical sided tanks than in the spherical tanks.

Overlaying the data with all tanks filled shows that at 20% fill level, the vertical sided tanks did not affect the vessel’s stability as greatly when compared to the spherical tanks. Between 50% and 60% fill levels, the spherical tanks’ impact upon the vessel becomes less than that of the vertical sided tanks. As the fill level increased past 60%, the stability of the spherical tanks was greater than that of the vertical sided tanks.

It is believed that the larger roll experienced by the vessel between 20% and 50% fill levels is due to the sphere having a greater possible surface area below 50% capacity compared to the vertical sided tanks. However, past 50% of capacity the space reduces as the sphere curves back on itself. Thus, experiencing a smaller surface area, and reducing the effect of the sloshing water. This data opens questions on the possibility of hybrid tanks with vertical sided tank sides in the lower section of the tank and opening to a spherical top half.

This also highlights the importance of correct tank designs with how the vessel and tank shall be operated. From the data produced for this paper, the frequency of the waves greatly impacts the vessel’s stability.

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