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Experimental analysis of an air cavity concept applied on a ship hull to improve the hull resistance

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Abstract

At the forefront of ship design is the desire to reduce a ship's resistance, thus being the most effective way to reduce operating costs and fulfil the international criteria for reduction in CO_2 emissions. Frictional drag is always proportional to the wetted surface of the vessel and typically accounts for more than 60% of the required propulsive power to overcome; hence the desire to reduce the wetted surface area is an active research interest. An initial full-scale sea trail on a vessel by introducing air as a lubricating medium has indicated 5-20% propulsive energy savings (DK-GROUP, 2010).

Following the report of the fundamental tests with the air cavity concept applied on a flat plate, which was conducted in the Emerson Cavitation Tunnel of Newcastle University (Slyozkin et al., 2014), this paper explores the same concept only this time applied on an existing container ship model to investigate whether it benefits in frictional drag reduction, whilst producing a net energy saving. The middle section of this 2.2m ship model was modified to accommodate a 0.43x0.09m air cavity in the bottom of the hull and then various model scale tests have been conducted in the towing tank of Newcastle University. The model experiments produced results ranging from 4-16% gross drag reduction. Upon applying scaling factors, it is estimated from the experimental results that around 22% gross energy could be saved in a full-scale application with just a 5% reduction in the wetted surface area.

Further complementary model tests were also conducted to explore the effect of the air cavity on the stability of the model and on the vertical motion responses in a regular head and following wave. While the cavity did not affect the vessel stability the motion response behaviour seemed to be affected non-linearly by the effect of the air cavity.

Keywords: Air Cavity, Frictional Drag Reduction, Energy Efficiency Design, Model Test, Stability, Non-linear Motion Response

1 Introduction

Recently, there has been a growing demand due to the ever changing economic, environmental and regulatory challenges that face the shipping industry, namely the implementation of the Energy Efficiency Design Index (EEDI) that has led to an increase in innovative designs to combat some of these challenges. The EEDI *'is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to be used in a specific ship design to the industry'* (IMO, 2014). In short, the EEDI is designed to promote innovative solutions towards meeting the efficiency levels, whilst maintaining the statutory build regulations of the chosen classification society.

One particular area of active research has been the introduction of air as a lubricating medium and is yet to be exploited to its full and commercial potential. There are three specific categories of air injection: Bubble Drag Reduction (BDR) (Kodama et al., 2000); Air Layer Drag Reduction (ALDR) (Elbing et al., 2013; Elbing et al., 2008); and Air Cavity (AC) (Foeth, 2008). Each option has had varying amounts and levels of experimental research conducted producing mixed results.

The BDR technique uses the injection of small air bubbles to reduce the skin friction along the boundary layer of the vessel. This technique in its experimental phase produced very promising results, with efficiency savings of up to 80%. However, the technique is heavily reliant on the hull form of the vessel i.e. flat bottomed. It also encountered problems in respect to the volume of bubbles required to reduce the skin friction on the full scale testing. It was stated that total resistance reduction in case of ballast and full load condition was 11% and 6% respectively (Hoang et al., 2009). However, this is a gross saving with little mention as to how much energy is required to generate sufficient volume of bubbles. Much of the continued research has been on methods for retaining the bubbles on the underside of the vessel to further optimise this technique. In more recent times this technique has been developed to reduce the energy required for bubble generation. The development of the Winged Air Induction Pipe (WAIP) allows for the water flow to over the hydrofoil surface; thus a low pressure region is produced on the upper surface of the hydrofoil. The negative pressure allows for a reduced pressure insertion of air

The ALDR method is similar to the BDR technique, but rather than producing a bubble mix, ALDR creates a thin continuous layer of air along the length of the underside of the hull. The layer of air is created by means of a slot at the forward end on the underside of the vessel. The thin layer of air traverses the vessel before it begins to break up into bubble form. This technique has been more recently advanced by adding a 'cavitator' to help initiate the air film (Zverkhovskyi, 2014). The 'cavitator' is designed to divert the impending flow of water on the underside of the vessel with a small slotted opening behind the 'cavitator' delivering the air supply. It was found that this method was particularly successful as it significantly reduced the amount of air flux required to generate the air film compared to the standard ALDR.

The ACS technique, also known as Partial Cavity Drag Reduction (PCDR) or Air Cavity (AC) is based on a series of openings on the underside of the vessel that are purged with air. Much of the research on this particular aspect has been in an experimental capacity with a particular focus towards how the air cavity is initiated, the interaction with the hull and body of water and how the release of air at the aft end of the cavity imparts on the hull. Experimental research as conducted by Slyozkin involved a plate with a backwards facing step (BFS) at the forward end of the incoming water flow and was tested in the Emerson Cavitation Tunnel (Slyozkin et al., 2014). In that experiment, air was delivered just behind the BFS to generate an air cavity and was then tested at varying flow conditions. The primary aim of this research was to determine the stability of the air cavity at the varying flow speeds, but also the volume of air required to initiate and maintain the cavity, thus the net energy savings. The optimum condition produced a profound result of 26% reduction in resistance. Slyozkin was able to conclude that if the cavity adds little to form drag, requires a low maintenance gas flux, tolerates flow perturbations and is stable over a wide speed range then this technique has great full scale potential in comparison to other air lubrication techniques.

Based on the conclusions by Slyozkin, the design of the cavity was imperative towards the success on assessing whether the introduction of an air cavity has a positive effect in producing a net energy saving. The work carried out by Slyozkin and Makiharju used a flat plate with a BFS testing arrangement (Makiharju et al., 2010; Slyozkin et al., 2014). The BFS allows for the initiation of the air cavity to occur more freely requiring less air pressure and flux. In both testing arrangements the forward edge of the plate has been horizontally neutral with a reasonable length before the BFS to allow for the flow to become uniform when travelling along the plate's surface.

Based on the equations of Ceccio and Makiharju the quantity of air that is required to generate the initial cavity and to then maintain are quite different (Mäkiharju et al., 2012). The equations were derived based on the results of flat plate experimentation and as such will not have a linear correlation between the experiments carried out by Ceccio and Makiharju and the proposed experimentation for this project. It has been observed that more air flux is required to initially generate the air cavity; however, much less is required to sustain the cavity. The Equation 1 is used to determine the air flux required to maintain the air cavity.

$$Q = W\,(0.00701\,U^2 - 0.0866\,U + 0.277) \qquad \textit{Equation 1}$$

Where Q is the air capacity required, m^3; W is the width of air cavity, m; U is the ship speed, m/s.

Within the above framework the main objective of the research study presented in this paper is to further advance the existing research on Air Cavity Drag Reduction based on the principal Author's MSc research (Butterworth, 2014), more specifically the research aims to develop a rudimental cavity form to determine whether air cavity is an efficient method of reducing frictional drag of a model container ship hull form through experimental resistance tests. Furthermore, to determine the optimum ratio of air flux to frictional drag reduction and to evaluate the change in frictional drag of the hull cavity and the hull form. Finally, to identify whether a cavity form has a significant impact on the stability of a vessel and to assess if and to what extent the cavity affects a vessel's sea keeping properties at a rudimentary level.

In order to achieve the above objectives Section 2 of the paper describes the experiments description which includes the model hull, experimental facility, set-up and test matrix. In Section 3 the results from the three sets of experiments are presented and discussed while in Section 4 the resistance test results are extrapolated to full-scale for the assessment of drag reduction benefit of the air cavity for a full-scale container vessel. Finally Section 5 presents the conclusions obtained from the study.

2 Experiments Description

2.1 Experimental setup

The emphasis of this experimentation was to determine how the cavity form integrates with the hull form to determine whether there is potential for further development of this particular technique aiding for drag reduction. The chosen method of experimentation was to utilise Newcastle University's towing tank facility. The towing tank is 37m in length, 3.7m in width and has a maximum carriage velocity speed of 3m/s. The towing tank also harbours the potential for wave generation to assess a vessel's seakeeping characteristics. Further recent details of this facility can be found in (Atlar, 2011).

The scale hull model used in the experiments was an existing 2.2m container ship model, which had initially been manufactured for the testing of the Inclined Keel Hull concept developed in Newcastle University (Seo, 2010; Seo et al., 2012). As such, this particular model had a relatively slim bulbous bow and a flat-bottomed hull form with no inclination as shown in Figure 1. This allowed the cavity form to be positioned horizontally with minimal inclination to prevent the flow from disturbing the effectiveness of the cavity form. The model was also appendage free. The main particulars of the vessel are shown in Table 1.

It is the intention that the size of the cavity should be of sufficient size to produce the intended result, but not such that the cavity designs produces form drag. Therefore, the design parameters for the cavity are given Table 2 and shown in Figure 2 where the air cavity is accommodated on the bottom of the hull.

In accordance with the wetted surface area and the design water line, DWL, it was the intention that the model would be simulated in a ballasted design condition and as such required the following ballasting arrangements. Note the Gifford dynamometer of the towing carriage to tow the hull model in the tank imposes a mass of 5.5kg on the centre of buoyancy on the vessel.

According to the requirements of this experiment, a constant and regulated air supply was to be delivered to the model throughout each of the proposed trials. The air was to be delivered by a compressor that had been secured onto the carriage of the towing tank. Due to the sensitivity of the measuring equipment on the carriage it was not possible to keep the air compressor running throughout the trial as the vibrations generated would be detected within the results. Therefore, it was necessary to split the motor unit and the air receiver unit. Essentially, the motor unit was connected to the air receiver when the carriage was in the dock position. The receiver was charged to 8 bars, isolated and then disconnected. This then eliminated any resonance being transmitted through the carriage to the model and the water. The air was then regulated by a flow meter, which had a split output and delivered the air to two outlets in the forward edge of the cavity form. Figure 3 to Figure 6 illustrate the details of the separated motor unit and receiver, the air inlets into the top of the cavity, the flow meters and a schematic of the whole air delivery system.

The vessel was to be filmed from a number of angles and perspectives to try and capture the full extent of the behaviour of the fluid in and around the cavity. A number of GoPro HD Hero 3 cameras were secured in various strategic positions to capture the behaviour around the cavity, the formation of the air cavity, the release of air from the underside and the release of air viewing from behind.

2.2 Test Matrix

It was the desire and one of the objectives of the project to obtain an elementary knowledge of an air cavity's interaction with a hull form. There were three key experimental aspects undertaken: incline test, variable air flux test and preliminary seakeeping test. Table 4 shows the type of the experiments, and the number of trials undertaken. For the resistance tests, each case was repeated for three times to ensure the reliability of the measured data.

2.3 Test Description

2.3.1 Stability tests

The stability of a vessel can be determined through a method of experimentation to determine the centre of gravity and the metacentric height by carrying out an inclination test as shown in Figure 7. This is an essential part in ship design, which includes stability characteristics for both laden and unladen conditions. These characteristics are likely to be altered if there is a change in the hull form, for example there is an air cavity underneath the vessel. Therefore, an incline test was done under laden conditions before any alterations were made to act as a datum. Once the hull had been modified, two incline tests were conducted: one with a water filled cavity; and other with an air-purged cavity. It was anticipated from the experiments as to whether the introduction of a cavity alters the stability of the vessel and whether this is improved or worsened. The incline test is comprised of a set of ballast weights moved in set increments and at these intervals the angle of heel was measured. By knowing the mass, the distance moved and the angle of heel it was possible to determine the metacentric height and the centre of gravity of the vessel.

2.3.2 Resistance test with varying Air Fluxes

Another important objective of this research project was to identify the effect of an air cavity on a hull form and also to determine the most optimum air flux, which would form the basis for the experimentation, in particular using Ceccio and Makiharju (2012) air flux equations as a basis for the design air flux.

Before any modifications were made to the vessel to accommodate the air cavity a series of datum tests were conducted. These included running the vessel by 0.1m/s increments from 0.6m/s to 1.5m/s to generate a speed-drag curve. Additionally, trials at the three design speeds of 0.617, 0.925 and 1.234 m/s were conducted as a datum for later comparison with the conditions by applying varying air fluxes. The speeds for this experiment have been calculated based on the Froude's law by using the following Equation *2*:

$$Fr = \frac{V_S}{\sqrt{gL_s}} = \frac{V_m}{\sqrt{gL_m}} \qquad \textit{Equation 2}$$

Where Fr is the Froude's number; V_S is the full-scale ship speed, m/s; g is the gravity acceleration, 9.81m/s^2; L_s is the length of the full-scale ship, m; V_m is the model-scale ship speed or the carriage speed, m/s; L_m is the length of the model-scale ship, m.

The Froude number for each speed was then used to determine the velocity of the model by Equation 3.

$$V_m = Fr\sqrt{gL_m} \qquad \textit{Equation 3}$$

Table 5 represents the respective speeds and Froude numbers and the model speeds. Table 6 details the experimental matrix for a single air cavity. Running at the three design speeds, each had a variation in air fluxes from no air to Ceccio's design air flux.

The term "no air" means that all air had been removed from the cavity and would be filled with water. This was to identify the detrimental effect on the performance that caused by the cavity form if not filled with air. The "Filled Cavity" term means that the cavity had been filled will air, but would not have a continual supply throughout the trial i.e. if any air escapes from the cavity then this will not be replaced. The design air flux is based on Ceccio's air flux equation, i.e. Equation 1 and is dependent on the carriage velocity.

2.3.3 Seakeeping tests

The seakeeping of a vessel in waves is important, as this will be the most challenging circumstance the vessel will likely to encounter. It was proposed that elementary testing in waves was to be conducted to establish whether the cavity form had any adverse effect on the motion performance of the vessel. The vessel was tested both against the waves (i.e. in head seas - 180^0) and with the waves (i.e. in following seas - 0^0) at the lowest design speed, 0.617m/s. Upon the cavity being fitted, the same experiments were carried out mainly in regular waves with the same wave particulars, which are presented in the frequency domain as shown in Figure 8, and the vessel vertical motion responses were evaluated to determine whether the cavity had any effect on them. The vessel was tested in its datum hull form condition and with the cavity fitted. The cavity was not be purged with air with the purpose of the experimentation to determine the worst case scenario i.e. a wave accessible cavity form. It was with the best experimental intentions that the vessel was started at the same time in relation to the wavelength. However, unless it was an automated computer driven process, it was not possible and therefore incurred a degree of error from the outset. This experimentation was designed to provide an insight into how the vessel performed in a seaway and was likely to provide the basis for further experimentation such as cavity design, air losses from the cavity, performance gains etc.

3 Experimental Results

3.1 Stability test

Three incline experiments were conducted and were all taken to approximately 10º of heel. This was the point at which the turn of the bilge started to become uncovered and any a further increase of heel may invalidate the results produced. Figure 9 graphically represents the results of the three incline experiments. The GZ curves for each of the test scenarios were all relatively similar and do not represent any particular characteristics that may prove detrimental to the operation of the vessel. The angles of heel are relatively low and could be extended further, but in the case of the air filled cavity, after a certain angle of heel the air begins to escape from the cavity and may introduce additional effects similar to the exposing of the bilge and as a result will accelerate the angle of heel as more of the vessel leaves the water.

3.2 Resistance test with varying air fluxes

As previously described, a speed curve was generated of the datum hull form to act as a basis for comparison. Figure 10 is a graphical representation of the datum speed curve from 0.6m/s to 1.5m/s.

Upon the datum hull form data being collaborated and the hull modified to accommodate the cavity form, a series of tests was conducted to determine the optimum variable air flux as per the testing matrix in Table 4. Table 7 presents the averaged results from the three trials for each conditions and the percentage of resistance reduction is also given in Table 8. Precision limit analysis was made for the uncertainty analysis based on the three repeat runs. ITTC procedure - Uncertainty Analysis, Example for Resistance Test, was followed. The precision limit varies under different conditions, generally below 5% under the lower speed and 1% under the higher speed.

Figure 11 is a graphical representation of the percentage of resistance reduction compared with the original datum hull form. Based on the test results it is clear to note that at the vessel design speed (0.617 m/s and 12 knots for the full-scale vessel) 15% of total resistance can be reduced if the air cavity can be continuously supplied with more than 7l/s. The slower travelling speeds offer the greatest potential for reducing the resistance of the vessel. It was observed upon reviewing the footage obtained that at the slower speeds, there was no air release from the cavity after it had been purged. Purging the cavity with air alone reduced the vessels resistance by 4%. These results were then improved further by increasing the delivered air flux to 2 and 7l/s. The higher air fluxes, 12l/s and the design air flux based on Ceccio's equation produced similar resistance reductions as the 7l/s. This means that the extra air being essentially delivered was wasted energy.

On the other hand, the air cavity becomes the less effective with the increasing speed. For the highest speed (1.235m/s and 24 knots for the full-scale vessel) the air cavity shows to be slightly detrimental for the total resistance and around 3% increase of the resistance can be observed even though it is continuously supplied with air. As shown in Figure 12, the air bubble is released from the starboard side when the speed gets higher, which might be the reason why the air cavity becomes less effective. The release of air from the Starboard side is likely due to be manufactured asymmetry of the model.

3.3 Seakeeping tests

The purpose of the qualitative seakeeping experiments carried out in this project was to develop an elementary understanding whether the cavity provides any added benefits or detrimental effects of the motion performance of the vessel. The experiments were intended to provide a small insight towards the overall seakeeping of the vessel as an original hull form and then how the cavity interacts with the vessel motions.

Figure 13 and Figure 14 show the comparative heave and pitch motion responses of the datum and cavity vessel at a particular regular head wave condition in the frequency domain, respectively. From these limited motion tests in the head sea condition at a particular regular wave, one can observe that the datum vessel responded to the wave excitation almost with the same frequency (1.4 Hz) of the incoming wave by taking into account the speed (encounter frequency) effect and confirming a linear response behaviour. However, this was not the case for the cavity vessel as the heave and pitch motion response occurred at a much lower, but at the same frequency as shown both in heave and pitch motion response. It is also interesting to note that both the heave and pitch responses of the cavity vessel were much higher than the datum vessel's heave and pitch responses.

The similar comparisons were also made in the following sea condition for the heave and pitch responses as shown in Figure 15 and Figure 16, respectively. It is a well-known fact that the following sea responses of any conventional vessel can be highly non-linear and this was also the case for the datum vessel. As shown in the figures the heave and pitch response frequency did not coincide with the expected encounter frequency (0.6 Hz). The similar non-linear responses were also observed with the cavity vessel although the response frequency was relatively near to the expected encounter frequency. However, this time the heave motion response amplitude of the datum and cavity vessels are similar while for the pitch response of the cavity vessel are still higher than that of the datum vessel.

As stated previously, although the motion tests were rather limited and demonstrative in nature to draw more informative conclusions they indicated that the air cavity may enforce non-linear behaviour as well as increasing the vertical motion behaviour. It is know from the seakeeping theory that the increase in vessel motions, particularly in pitch, will make major contribution to the increase of the added wave resistance of a vessel. This may bring the question of applying air cavity may be counterproductive for vessels operating in rough seas.

4 Full-scale power prediction

Carrying out a model scale experiment provided a fundamental understanding for the effect of air cavity. This experiment can provide the basis for the resistance prediction for full-scale vessels. It is also necessary to take the results generated from the model tests and apply a series of scaling factors and coefficients to estimate the full-scale power requirements and to determine the fiscal incentives that could be achieved.

For the purpose of predicting the full-scale ship resistance, ITTC recommended procedures can be followed in this process (ITTC, 2011). However, assuming that the air cavity actually reduced the wetted surface area for the part of the frictional resistance, the total resistance for the model-scale ship can be formulated as in Equation 4.

$$R_{TM} = C_R \frac{1}{2} \rho_W V_M^2 S_{WM} + (1+k) C_{FM} \frac{1}{2} \rho V_M^2 S_{(W-A)M}$$ *Equation 4*

Where R_{TM} is the total resistance of the model, in N; C_R is the residual resistance coefficient which is the same for both model and full scale vessel; $\rho_W$is the fresh water density, 997kg/m^3; V_M is the velocity of the model, in m/s; S_{WM} is the wetted surface area of the model without considering the air cavity, 0.7026m^2; $1+k$ is the form factor, which is 1.12 for this vessel; C_{FM} is the frictional resistance coefficient of the model; $S_{(W-A)M}$ is the wetted surface area of the model considering the air cavity, 0.6639m^2 if the air cavity is purged with air and 0.7026m^2.

C_F is the frictional resistance coefficient calculated by ITTC 1957 frictional resistance coefficient equation which is shown in Equation 5.

$$C_F = \frac{0.075}{(\log Re - 2)^2} \quad \textit{Equation 5}$$

Where Re is the Reynold's number calculated by the following Equation 6.

$$Re = \frac{VL}{\upsilon} \quad \textit{Equation 6}$$

Where V is the ship speed; L is the ship length; υ is the kinetic viscosity, and used 1.307E-6 and 1.139E-6 m^2/s for the model and full-scale, respectively.

Following the above equations, the residual coefficient can be derived from the following Equation 7.

$$C_R = \frac{R_{TM} - (1+k)C_{FM}\frac{1}{2}\rho V_M^2 S_{(W-A)M}}{\frac{1}{2}\rho V_M^2 S_{WM}} \quad \textit{Equation 7}$$

For the full-scale vessel, certain correlation allowance factor (C_a) should be applied on the prediction, which can be achieved from the Equation 8.

$$C_a = 0.006 * (LWL + 100)^{-0.16} - 0.00205 \quad \textit{Equation 8}$$

Where LWL is the ship length at waterline, 221m.

Therefore the total resistance of the full-scale vessel can be given as in Equation 9.

$$R_{TS} = (C_R + C_a)\frac{1}{2}\rho_S V_S^2 S_{WS} + (1+k)C_{FS}\frac{1}{2}\rho V_S^2 S_{(W-A)S} \quad \textit{Equation 9}$$

Where ρ_S is the sea water density, 1025kg/m^3; V_S is the velocity of the full-scale ship; S_{WS} is the wetted surface of the full-scale ship; C_{FS} is the frictional resistance coefficient of the full-scale ship; $1+k$ is the form factor, which is not related to the wetted surface area, 1.12 for this vessel; $S_{(W-A)S}$ is the wetted surface area of the full-scale ship considering the air cavity.

From the above equations it was possible to generate an estimation towards the full-scale power requirements for the vessel, which is given in Table 9. From this calculation, around 21% power can be saved when the vessel is sailing at 12 knots with 7l/s air delivery. However, as the vessel's speed increases, the air cavity becomes less effective and detrimental for the performance.

It should be born in mind that the above power calculations are a gross estimation and the estimation method has largely inherited from the traditional hull form, which needs to be improved by more model-scale and full-scale trials with the air cavity vessel data. This prediction only aims to provide a rudimentary indication for the percentage of the power saving. On the other hand, this prediction does not take into account the power required to generate the air delivery. There are a number of options available including air compressor, exhaust emissions and turbo power take off that may be able to provide the required air. Based on the statement by DK Group, only 0.5-1% of propulsive power is required to keep the air cavity sustained and also depends on the air flux that needs to be delivered (DK-GROUP, 2010).

5 Conclusion

In this paper three sets of experimental trials, which are static stability, resistance and motion response tests, have been presented with a container ship model in order to investigate the performance prediction of introducing an Air Cavity into a model hull form. Accordingly the following conclusions can be drawn from the experimental analysis:

1. The introduction of a cavity form has little to no impact on the static stability of a vessel, regardless of whether the cavity is filled with air or not. When the cavity was purged with air, there was a release of air from the cavity as the angle of heel approached 10˚. However, this didn't appear to have an effect on the static stability of the vessel.

2. The introduction of a cavity form increased the hull resistance 10% as compared to the datum hull form's resistance. It was the intention of the research that a rudimentary cavity form would be created that would not only provide a suitable means of delivering the air supply, but to also create minimal disturbance to the hull form. For greater improvement, development into the cavity form may produce a lower resistance increase as compared to the datum hull form.

3. Purging the cavity with varying levels of air flux at different vessel speeds has produced a nonlinear result. It was assumed that as the air flux increased, the exiting bubble flow would aid in the resistance reduction. However, it appeared that this began to plateau between 7l/s and 20l/s at 0.617m/s. Essentially, the increased air flux was wasted energy. Simply purging the cavity with air generated a resistance saving of 4% by simply reducing the wetted surface area by 5%. As the vessel speed was increased, the level of resistance was only marginally decreased by at 0.926m/s and increased for 1.235m/s. This application is suggested to be more suited to slower operating speed when the frictional resistance is dominant.

4. Limited and comparative motion response tests in a particular regular head and following wave condition indicated that the application of the air cavity may induce non-linear vertical motion behaviour with increase responses that may in turn increase the resistance in waves.

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Figures

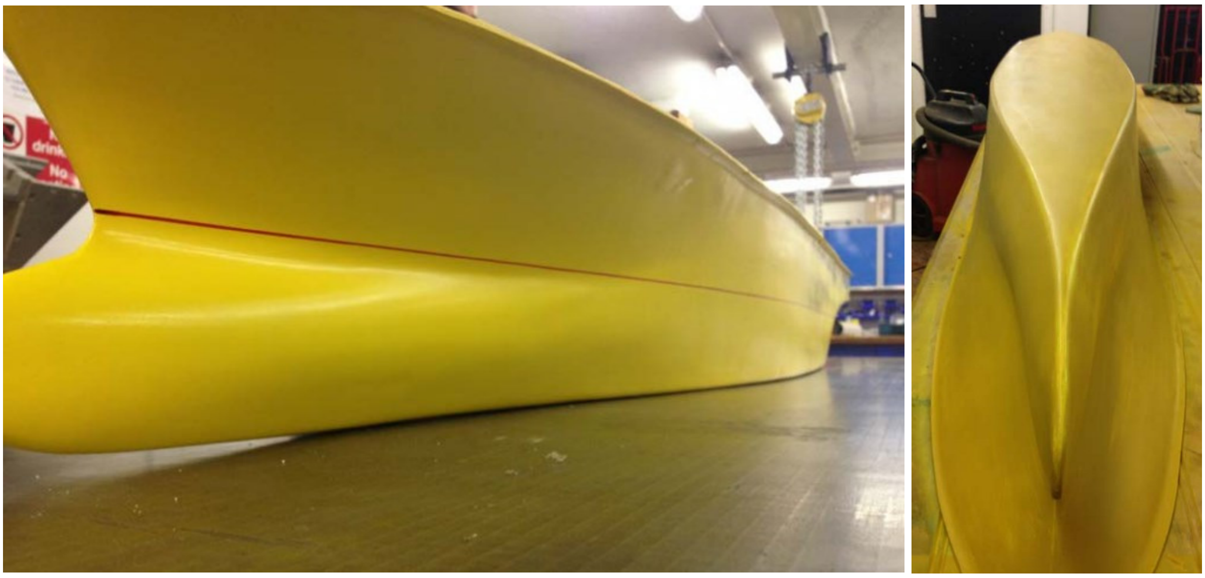

Figure 1 Scaled datum hull model (left is the side view and right is the view for the bottom)

Figure 2 Air cavity accommodated on the bottom of the hull – cavity parameters can be found in Table 2.

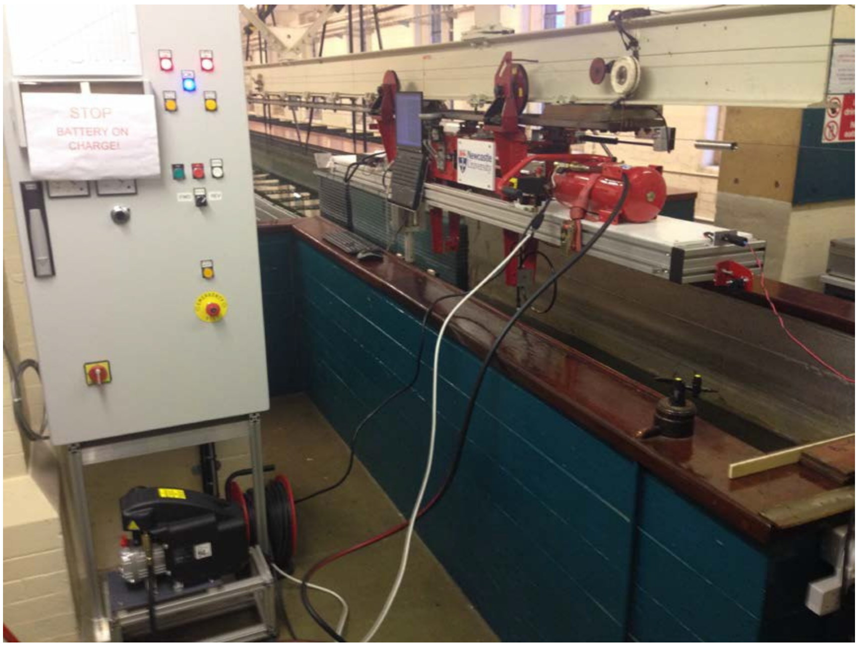

Figure 3 Motor unit and air receiver unit configuration

Figure 4 Air inlets into the top of the cavity

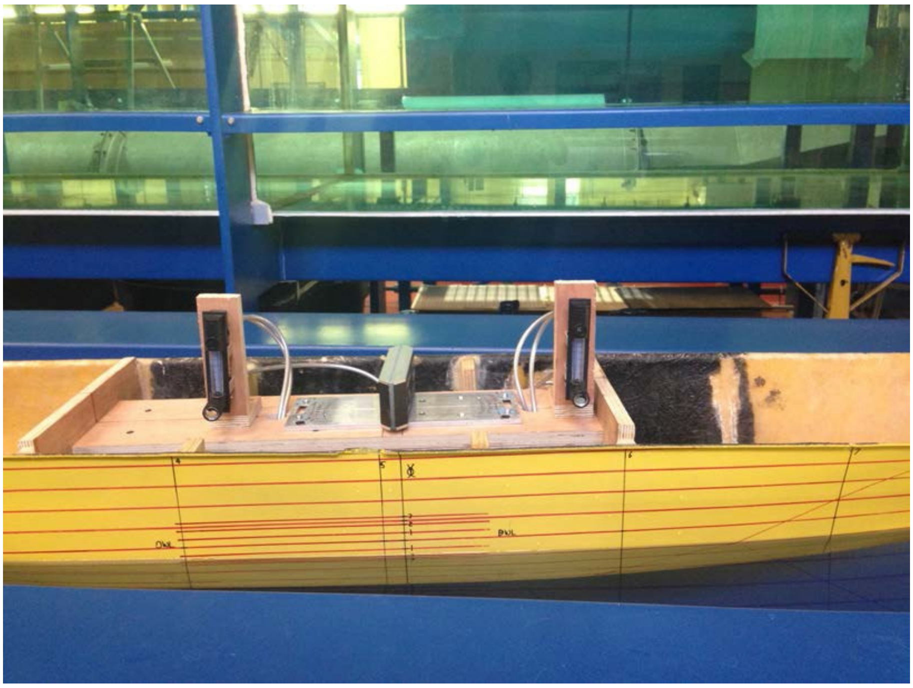

Figure 5 Flow splits and meters

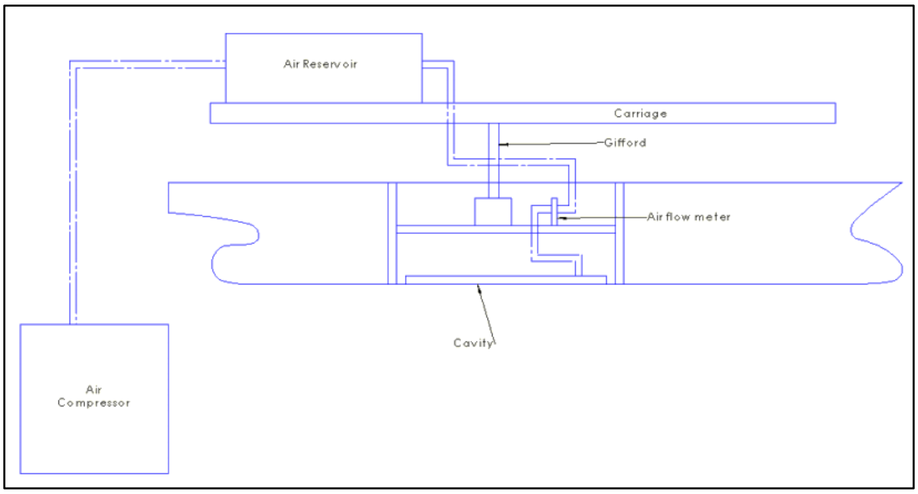

Figure 6 Schematic of air delivery system

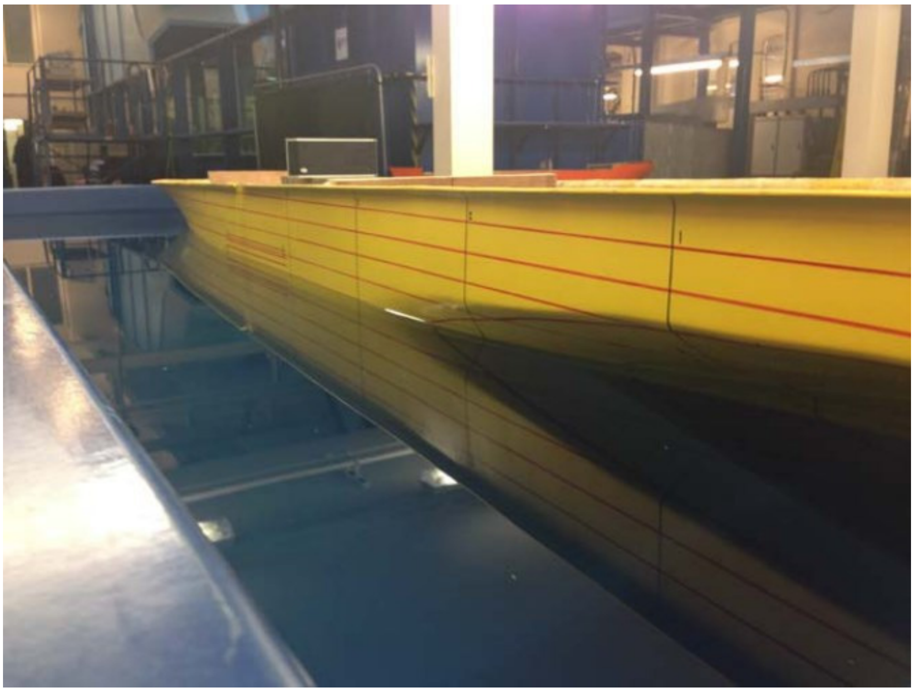

Figure 7 Static stability test in stability tank

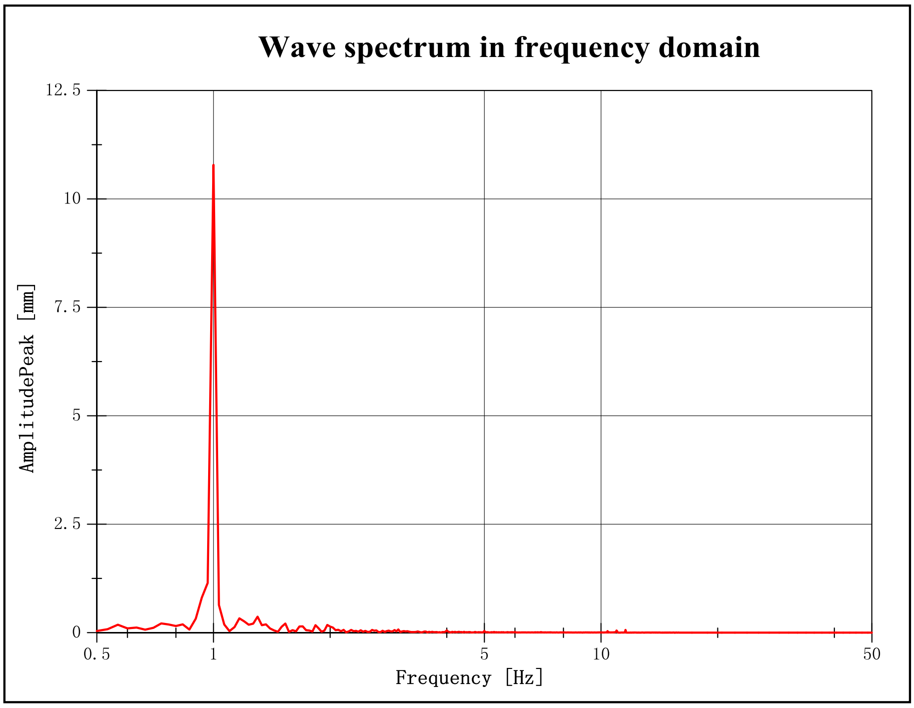

Figure 8 Wave spectrum used for seakeeping test

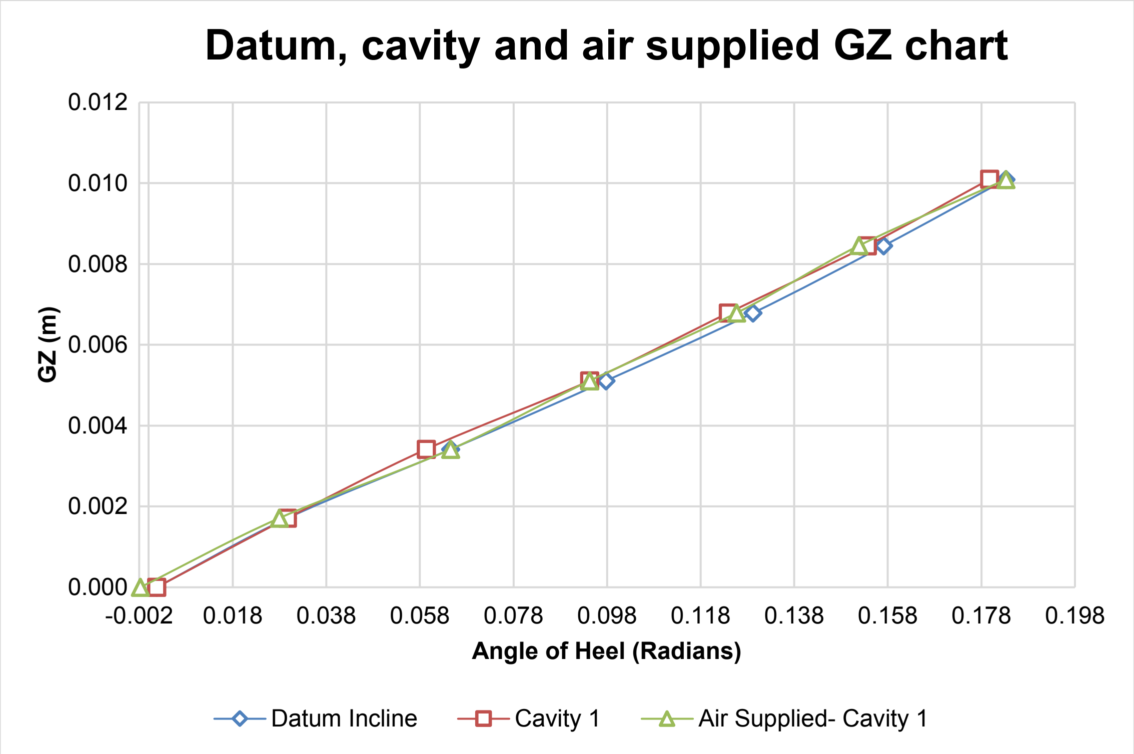

Figure 9 The results of the three incline experiments

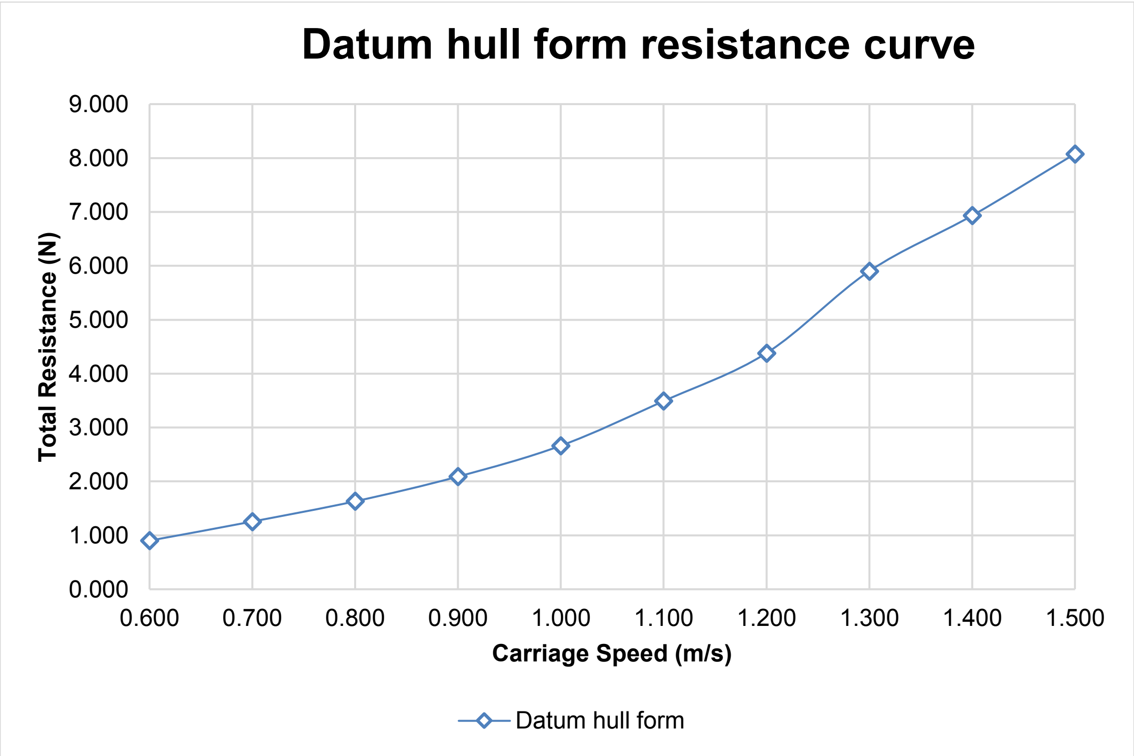

Figure 10 Resistance curve of Datum hull form

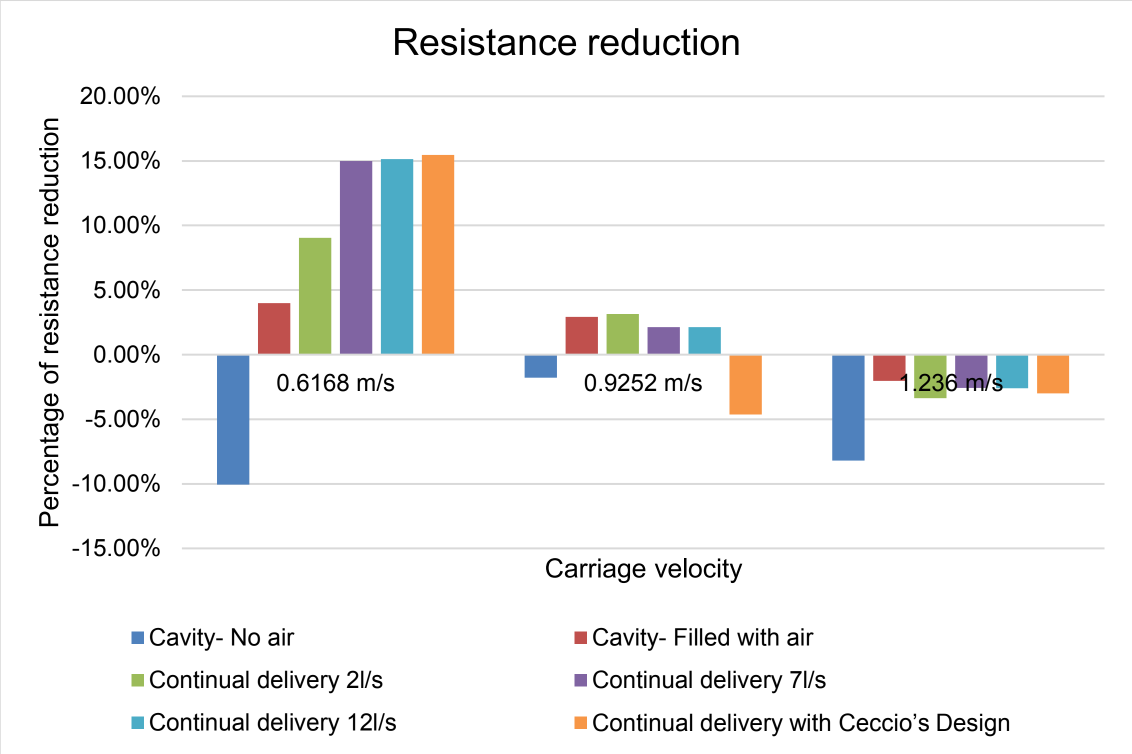

Figure 11 Percentage of resistance reduction compared with the datum hull form

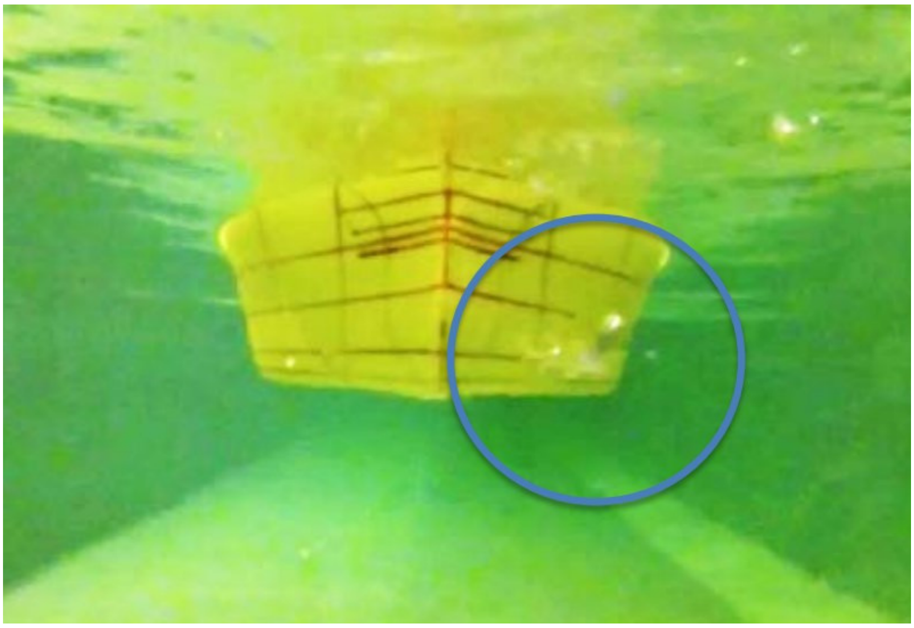

Figure 12 Air bubble escaped from the starboard side (1.235m/s with 12l/s air delivery)

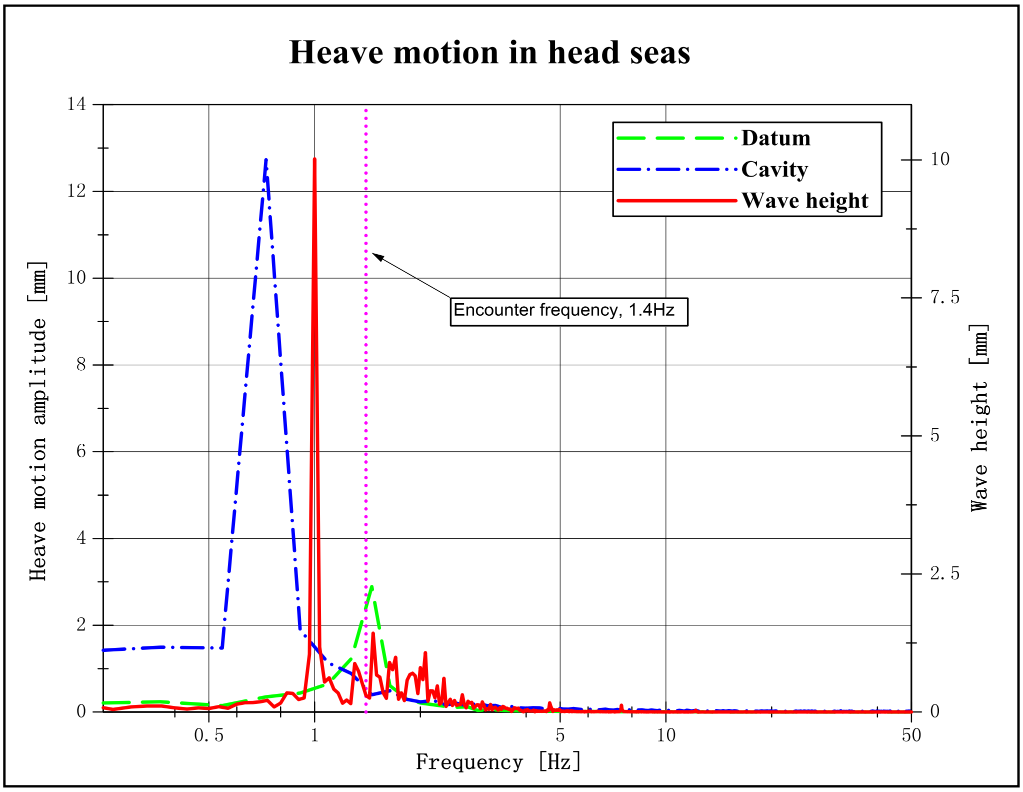

Figure 13 Comparative frequency domain heave motion responses in head seas

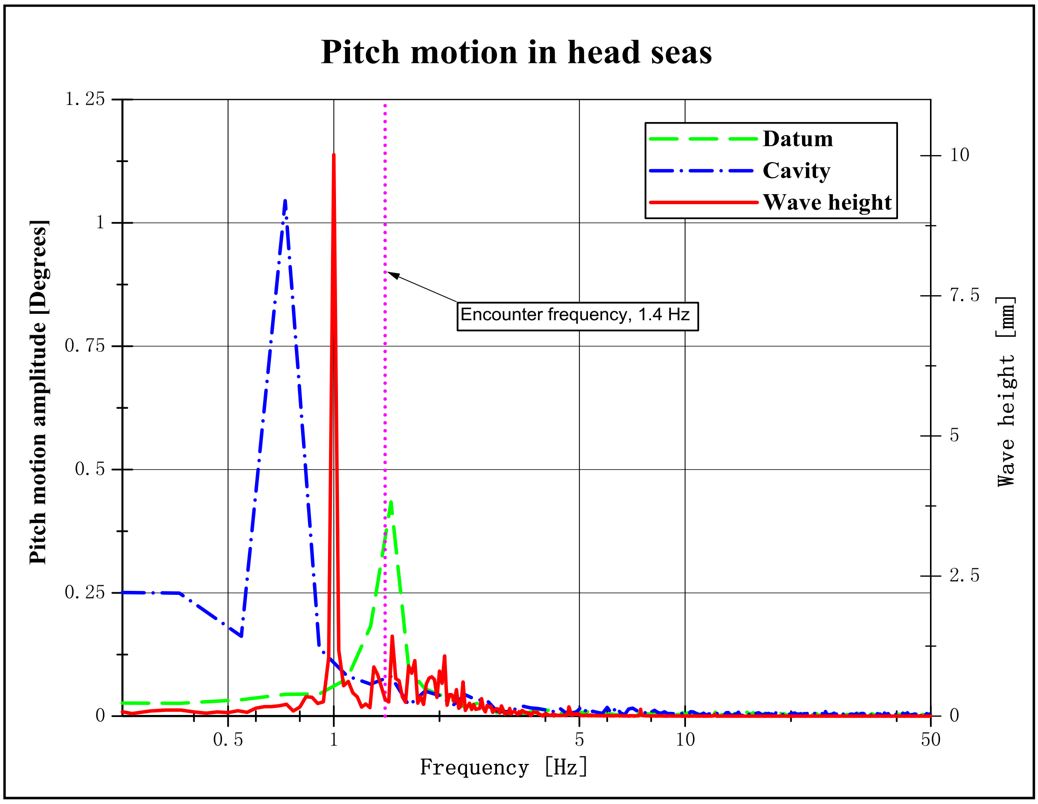

Figure 14 Comparative frequency domain pitch motion responses in head seas

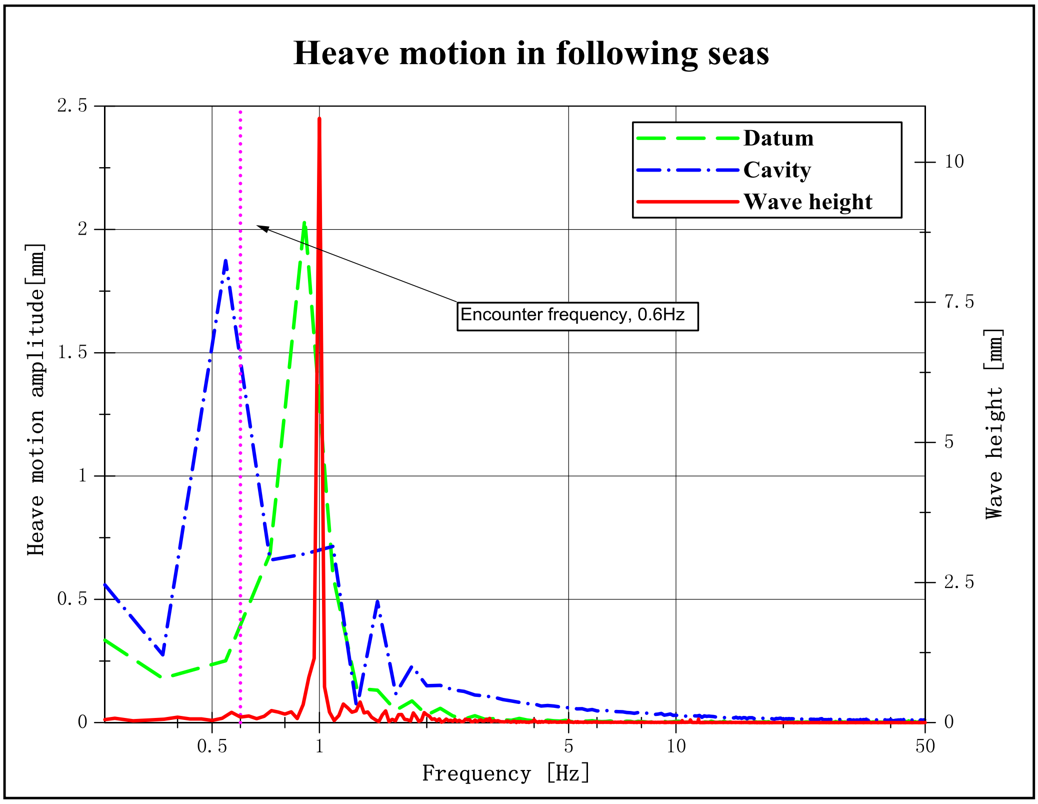

Figure 15 Comparative frequency domain heave motion responses in following seas

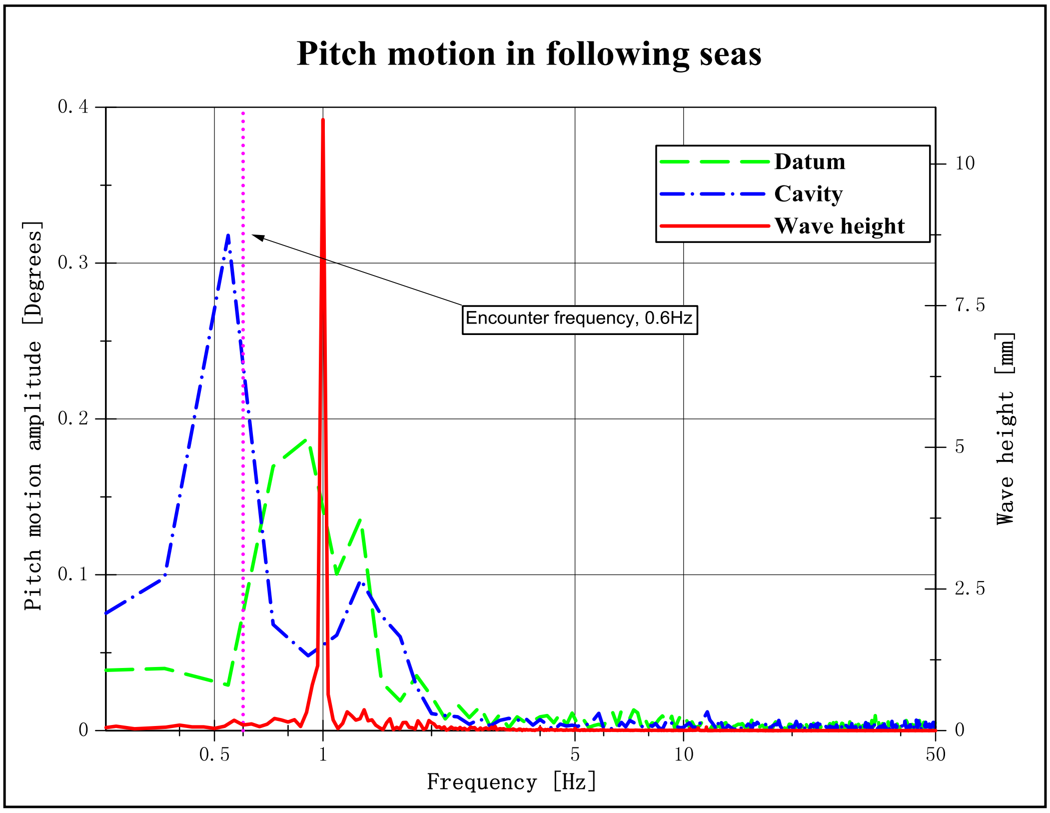

Figure 16 Comparative frequency domain pitch motion responses in following seas

Tables

Table 1 Main particulars of the model

Definition	Symbol	Value	Unit
Scale Ratio		1:100	
Waterline Length	LWL	2.21	m
Waterline Beam	BWL	0.316	m
Draft	T	0.1	m
Length	LPP	2.4	m
Wetted Surface Area		0.7026	m^2
Displacement	Δ	44.42	kg
Block Coefficient	C_b	0.64	
Prismatic Coefficient	C_p	0.70	

Table 2 Parameters of cavity form

Description	Value	Unit
Length	0.43	m
Width	0.09	m
Area	0.0387	m^2
Wetted Surface Area of Model	0.7026	m^2
Reduction in Wetted Surface Area	5.5%	

Table 3 The required masses required to displace the model to the DWL

Description	Value	Unit
Model	10.3	kg
FWD Ballast	17.5	kg
AFT Ballast	11.1	kg
Gifford Mass	5.5	kg
Total Mass	44.4	kg

Table 4 Test matrix

Type of trial	Description	No. of trials
Incline (stability)	Datum hull form	1
	Cavity- No air	1
	Cavity- Filled with air	1
Resistance/variable air flux	Datum hull form, 0.617m/s	3
	Datum hull form, 0.925m/s	3
	Datum hull form, 1.235m/s	3
	Cavity- No air, 0.617m/s	3
	Cavity- No air, 0.925m/s	3
	Cavity- No air, 1.235m/s	3
	Cavity- Filled with air, 0.617m/s	3
	Cavity- Filled with air, 0.925m/s	3
	Cavity- Filled with air, 1.235m/s	3
	Continual delivery 2l/s, 0.617m/s	3
	Continual delivery 2l/s, 0.925m/s	3
	Continual delivery 2l/s, 1.235m/s	3
	Continual delivery 7l/s, 0.617m/s	3
	Continual delivery 7l/s, 0.925m/s	3
	Continual delivery 7l/s, 1.235m/s	3
	Continual delivery 12l/s, 0.617m/s	3

	Continual delivery 12l/s, 0.925m/s	3
	Continual delivery 12l/s, 1.235m/s	3
	Continual delivery with Ceccio's Design 20l/s, 0.617m/s	3
	Continual delivery with Ceccio's Design 18l/s, 0.925m/s	3
	Continual delivery with Ceccio's Design 16l/s, 1.235m/s	3
Seakeeping test	Datum hull form, 0.617m/s in head seas (180°), f= 1Hz; H=10mm	1
	Datum hull form, 0.617m/s with in following seas (0°), f= 1Hz; H=10mm	1
	Cavity- No air, 0.617m/s in head seas (180°), f= 1Hz; H=10mm	1
	Cavity- No air, 0.617m/s in following seas (0°), f= 1Hz; H=10mm	1

Table 5 Froude numbers and model test speeds

Name	Ship Speed (Knots)	Speed (m/s)	Froude No.	Model Speed (m/s)
V1	12	6.17	0.127	0.617
V2	18	9.25	0.191	0.925
V3	24	12.35	0.254	1.235

Table 6 Experimental matrix for air cavity

Speed (m/s)	Air flux (l/s)					
0.617	No Air	Filled Cavity	2	7	12	Design – 20
0.925	No Air	Filled Cavity	2	7	12	Design – 18
1.235	No Air	Filled Cavity	2	7	12	Design – 16

Table 7 Averaged resistance readings at varying air flux and speeds

Speed (m/s)	0.617		0.925		1.235	
	(N)		(N)		(N)	
Cavity- No air	1.056	4%	2.128	1%	4.492	1%
Cavity- Filled with air	0.921	4%	2.029	1%	4.235	1%
Continual delivery 2l/s	0.873	4%	2.024	2%	4.292	3%
Continual delivery 7l/s	0.816	4%	2.045	1%	4.259	1%
Continual delivery 12l/s	0.814	7%	2.046	1%	4.259	0.4%
Continual delivery with Ceccio's Design	0.811	6%	2.187	1%	4.276	0.4%

Table 8 The percentage of resistance reduction against the original datum hull form

Speed	0.617 m/s	0.925 m/s	1.235 m/s
Cavity- No air	-10.05%	-1.79%	-8.20%
Cavity- Filled with air	4.00%	2.92%	-2.02%
Continual delivery 2l/s	9.03%	3.14%	-3.38%
Continual delivery 7l/s	14.98%	2.14%	-2.59%
Continual delivery 12l/s	15.15%	2.13%	-2.60%
Continual delivery with Ceccio's Design	15.46%	-4.64%	-3.00%

Table 9 Full-scale resistance prediction

Name	Full-scale ship residual resistance	Full-scale ship frictional resistance	Correlation allowance	Total resistance	Effective power	Power saving
Unit	(N)	(N)	(N)	(N)	(MW)	(%)
12 knots						
Datum hull form	273665.40	229692.77	45607.65	548965.82	3.39	0.00%
Cavity- No air	372783.01	229692.77	45607.65	648083.43	4.00	-18.06%
Cavity- Filled with air	273472.95	217041.04	45607.65	536121.64	3.31	2.34%
Continual delivery 2l/s	223816.48	217041.04	45607.65	486465.17	3.00	11.39%
Continual delivery 7l/s	165184.84	217041.04	45607.65	427833.52	2.64	22.07%
Continual delivery 12l/s	163488.50	217041.04	45607.65	426137.18	2.63	22.37%
Continual delivery with Ceccio's Design	160393.97	217041.04	45607.65	423042.65	2.61	22.94%
18 knots						
Datum hull form	675437.27	492622.64	102750.35	1270810.25	11.77	0.00%
Cavity- No air	713969.87	492622.64	102750.35	1309342.85	12.12	-3.03%
Cavity- Filled with air	693799.70	465488.43	102750.35	1262038.47	11.68	0.69%
Continual delivery 2l/s	689070.51	465488.43	102750.35	1257309.29	11.64	1.06%
Continual delivery 7l/s	710588.32	465488.43	102750.35	1278827.09	11.84	-0.63%
Continual delivery 12l/s	710804.21	465488.43	102750.35	1279042.99	11.84	-0.65%
Continual delivery with Ceccio's Design	1041446.39	465488.43	102750.35	1609685.16	14.90	-26.67%
24 knots						
Datum hull form	1792143.27	848435.47	183141.12	2823719.86	34.90	0.00%
Cavity- No air	2142020.90	848435.47	183141.12	3173597.50	39.23	-12.39%
Cavity- Filled with air	2015022.76	801702.69	183141.12	2999866.58	37.08	-6.24%
Continual delivery 2l/s	2072817.55	801702.69	183141.12	3057661.36	37.79	-8.28%
Continual delivery 7l/s	2038931.89	801702.69	183141.12	3023775.70	37.37	-7.08%
Continual delivery 12l/s	2039353.40	801702.69	183141.12	3024197.22	37.38	-7.10%
Continual delivery with Ceccio's Design	2056697.19	801702.69	183141.12	3041541.00	37.59	-7.71%