Wake of a catamaran navigating in restricted waters

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ABSTRACT: High speed catamaran ferries are used throughout the world in confined waters, such as rivers and ports. Wake from these and other small vessels have a variety of effects on the waterways, including deterioration of banks, damage to structures and other vessels, and danger to people close to the shore. An existing code has been used to predict the wake produced by different catamaran hulls in a channel. A CFD study determined the wave heights so that the pressure distribution used in the existing code could be calibrated to accurately predict the wave heights for each hull. Design of experiments methods were utilised to identify the main and interacting effects of the hull characteristics varied between the hulls. Comparison between the existing code and CFD results showed that slight differences between hull characteristics gave different wave heights and these differences could be accounted for by calibrating the pressure distribution. Design of experiments analysis highlighted that of the four factors (beam, demi hull beam, bow keel rake and bow entry angle) demi hull beam had the largest effect on the wave heights and for the values tested, the combination of beam and demi hull beam, i.e. hull spacing, did not have a higher interacting effect than other combinations.
Keywords: Catamaran, Funwave, Boussinesq, Wake, Wash

1 INTRODUCTION

Maritime transportation has become an essential part of modern society, however there are many negative environmental impacts which people are now seeking solutions for. The main motivations behind investigating this topic include: the safety of people and property in coastal environments, the effect of wake wash on the coastal environment, the social and economic effects due to changes or closure of ferry routes and, lastly, the development of an innovative design tool for naval architects and researchers to study the effects of different ship designs on wake wash.

The main objectives of this study were to predict the wakes generated by a set of catamaran designs and their propagation over a given bathymetry using an adapted Funwave code, as well as analysing the main and interacting effects of the *Beam*, *Demi-Beam*, *Bow Keel Rake* and *Bow Entry Angle* on the wave height and wave energy of the wake wash. These were identified by completing a Design of Experiments analysis in conjunction with the CFD studies. Technical data and support for this research were provided by Incat Crowther, Sydney, as well as various faculties within Instituto Superior Tecnico.

The preliminary stage of the research included a CFD study of a single 29.6m hull in a deep-water channel as a monohull and as a catamaran. With this data the pressure distribution used in the Funwave code could then be calibrated by running multiple simulations for different 'applied' drafts until agreement was found between the Funwave and CFD results.

The main stage of research included 8 CFD simulations of catamarans in a deep-water channel. The hulls were varied according to a half factorial study of four factors mentioned above, each with two levels. These hull models were provided by Incat Crowther, a naval architecture firm based in Sydney, Australia. Using the results of the 8 CFD simulations, the different hulls could be modelled in the Funwave code accurately. Once the 'applied' drafts were calibrated for a deep-water channel, the same Funwave code could be re-run for a more complex bathymetry.

In the final stage of the research the results of the CFD study were analysed using the DOE methodology and the main and interacting effects were determined.

2 BACKGROUND THEORY

2.1 *Wake Wash Studies*

Today wake wash is well understood, and the form can be predicted with accuracy. In general, the wave pattern generated is more affected by the vessel's speed/depth ration than the vessel's form. The *Length Froude Number* and *Depth Froude Number* are both useful dimensionless equations which can be used to predict the wave wash form.

Length Froude Number,

$$Fr_L = \frac{u}{\sqrt{gL}} \tag{1}$$

Depth Froude Number,

$$Fr_h = \frac{u}{\sqrt{gh}} \tag{2}$$

When the vessel speed corresponds to a depth Froude number less than approximately 0.75, the speed is said to be sub-critical. As the Froude depth number approaches one ($0.75 \leq \mathrm{Fr_h} < 1.0$) the speed is said to be trans-critical and when the Froude depth number is one it is called critical. Speeds corresponding to Froude depth numbers above one are termed super-critical.

For vessel speeds within the sub-critical region, all vessels produce the wake pattern called a Kelvin Wave Pattern. It consists of two wave types, transverse and divergent. Transverse waves propagate parallel to the sailing line behind the ship. The height of the waves is heavily dependent on the vessel's length-displacement ratio. Divergent waves propagate at around 35 degrees from the sailing line, from the bow and stern of the ship. The divergent wave trains form a Kelvin Wedge with an angle of 19 degrees each side of the sailing line. This angle termed the wave angle and the propagation angle (19 and 35 degrees, respectively) are dependent on the Froude depth number. Havelock [1] showed that the wave angle is around 19 degrees until the Froude depth number approaches 0.75, where it rises sharply peaking at 90 degrees for a Froude depth number of one. The transverse waves also merge with the divergent waves. Once the Froude depth number becomes super critical the transverse waves disappear and the divergent waves take on a more acute angle (dependent on the ship's velocity).

Wave energy is a key factor that can be used to compare the wake wash of vessels, particularly with respect to is potential to be destructive to coastal environments. Wave Energy can be calculated using the formula.

Wave energy per wavelength per unit width of wave crest in deep water [2],

$$E = \frac{\rho g^2 H^2 \ T^2}{16\pi} \tag{3}$$

Over the past decades, with the improvement in experimental tools, there have been numerous, full-scale and model-scale, wake wash studies completed. These studies range in scope from measurements taken at a specific location [3] to the development of empirical formulas that can estimate the wake characteristics at sub-critical, trans-critical and/or super-critical speed regimes.

Fox et al. [4] using data collected in the NY state waterways, linked the hull characteristics of the ferries used at the time to the wake wash characteristics, specifically the displacement length ratio to wake wash heights.

Kirkegaard [5] made a similar study of ferries in the coastal areas of Denmark, including catamarans with service speeds between 35 and 45 knots. The report outlines the underlying concern and driving force behind the destruction of coastal environments by high speed craft, which is; "the relative short duration of wave events caused by high speed craft do not allow the natural balancing currents that return sediment to approximately original position to occur" [5].

More recent studies have again used full and model scale experiments to understand higher level phenomenon and wake wash characteristics. Studies by Macfarlane [6] and Robbins [7] are recent examples.

2.2 *Wave Propagation Studies*

Peregrine [8] first derived the, now standard, Boussinesq equations for variable water depth, by using a depth-averaged velocity as a dependent variable. The equations are for shallow water nondispersive linear wave propagation. The standard Boussinesq equations assume weak frequency dispersion effects, making them invalid in intermediate water depth and deep water.

Many numerical models have been based on the derivations of Peregrine and have compared well with experimental data [9], [10]. Nwogu [11] derived the extended Boussinesq equations which improved the dispersive properties of propagating waves, allowing simulation of wave propagation from deep to shallow water with accuracy.

Wei & Kirby [12] developed a numerical model based on these extended Boussinesq equations and proved its accuracy for a range of water depths. Kirby et al., [13] later developed the program Funwave. Nacimento & Maciel [14] adapted the program to model the propagation of ship generated waves. In this model the pressure distribution is added to the momentum equations to simulate ship wave generation[1]. Naciemento & Maciel [15] created the code Funwave+ship, an extension of the adapted Funwave program, to simulate the interaction of two wave trains travelling either side by side (but at different speeds) or away from each other. Rodrigues et al. [16] adapted the model of Nacimento & Maciel [14] to simulate ship waves propagating over a sloping bottom using the pressure distribution suggested by Li & Sclavonous [17]. Similarly, Torsvik & Soomere [18] used a code based on the extended Boussinesq equations on the highly irregular bathymetry of Tallin Bay, Estonia. The pressure distribution used by Torsvik and Soomere was rectangular, with roughly the length and breadth equal to the ship, and pressure distribution equal to the hydrostatic pressure of the ship's hull.

2.3 *Computational Fluid Dynamics Studies*

The use of Computational Fluid Dynamics codes to study the area of wake wash has grown in the last

[1] See the work of [12], [13] and [16] for descriptions of the relevant theory and equations used in the adapted Funwave code.

decades. In many studies the aim is to predict the wave making resistance of the ship, which has led to studies on wake wash. Tarafder & Suzuki [19] used a potential based panel method to study the effects of wave interference and hull separation on the wave making resistance of a Wigley hull catamaran in deep water. From this study, they noted that the magnitude of the wave profile on the inner side of the catamaran is much larger due to wave interference, and that at higher speeds and hull separations (s/L>0.4) interference effects were negligible. Echoing the results found by Tarafder and Suzuki, Nizam et al. [20] found, in their paper on a numerical study of wave making resistance of a pentamaran in unbound water using a surface panel method, that at higher speeds (Fn>0.8) interference between hulls was greatly reduced. He et al. [21] also considered the wave interference effects on the far field wake characteristics of both monohull and catamarans, noting that the hull shape has a larger impact on the wave heights, while the kinematics of the ship have more influence on the shape of the wake field.

2.4 Design of Experiments Methodology

Successfully implemented Design of Experiments (DOE) methodology can yield large gains in terms of time and effort saved by reducing the number of experiments required to obtain results for multiple factors. Factorial studies relate to experiments where more than one factor may be important and Factorial Experimental Design (FED) is applied when each combination of factor levels must be tested [22]. It is evident that this can be applied to the area of naval engineering where there are always multiple factors affecting any situation. FED has also been used in optimisation studies, it was pioneered by Genichi Taguchi, a Japanese engineer, in the 1950s. When there are multiple factors to be considered, engineers will usually use a fractional factorial study. A fractional factorial study is where only some combinations of the factorial study are tested. The combinations are chosen specifically to allow the main and interacting effects to be separated and studied. This means that the engineer only needs half or even a quarter of the tests usually required for the full factorial study, while still obtaining an accurate perspective of which factors have the largest effects.

3 PRELIMINARY STUDY

3.1 Computational Fluid Dynamics Study

The CFD simulations where made using the RANSE solver STAR CCM+, which is a commercially available program developed by CD ADAPCO. Since all the hulls studied have similar characteristics, the same model could be used each time. The domain size was chosen based on multiples of the ships length. The domain stretched from four ship lengths aft of the ship, to 1.5 ship lengths forward of the bow. The domain width was also 1.5 ship lengths measured each side of the sailing line, the water depth was 2 ship lengths below the surface and the top of the domain was 0.5 ship lengths above.

The grid used was a uniform prism mesh with custom surface mesh sizes at the boundaries and two volumetric controls at the water surface. The hulls used prism layers and Two Layer all y+ Wall Treatment. The grid size at the exterior surfaces were 5m, while the smallest grid size on the surface of the hull was 0.05m. The boundary growth rate was set to slow, which yielded a growth pattern shown in Figure 1 below. The near wall prism layer thickness was set to 0.01m and the prism layer thickness was set to 0.04m, where 3 prism layers were used. A convergence test was made for the preliminary hull used in this study. Three simulations were run: one at 10 million cells, one at 4 million cells and one at 2.8 million cells. The test highlighted that for a simulation with around 4 million cells, the results were very close to those of 10 million cells, suggesting that 4 million cell simulations were sufficiently accurate to use.

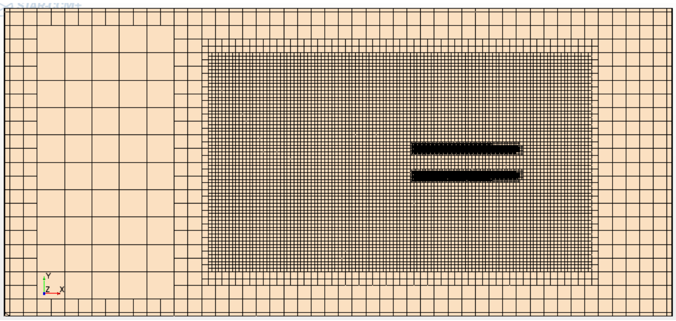

Figure 1: CFD Grid Growth Pattern

The model included the boundaries: inlet, outlet, side walls, top, bottom and hull surfaces. The side walls, top and bottom boundaries used the wall type with the slip Shear Stress Specification utilised. The hull also utilised the wall type, but used the non-slip Shear Stress Specification and a smooth wall surface specification. The inlet used a velocity inlet type with a current of 10m/s for both air and water in the preliminary study and 12.86 m/s in the main study. The outlet used a pressure outlet type, utilising the hydrostatic pressure from the Volume of Fluid model. The Boundary conditions are summarised in Table 1.

Table 1: CFD Boundary Conditions

Boundary	*Type*	*Specifications*
Side Walls, Top & Bottom	*Wall*	*Slip*
Hulls	*Wall*	*Non-Slip*
Inlet	*Velocity Inlet*	*10m/s – Preliminary study* *12.86m/s – Main Study*
Outlet	*Pressure Outlet*	*Hydrostatic Pressure of VOF*

The simulation used the Volume of Fluid model with the FlatVOFWave option selected, creating a flat initial water surface with inlet and outlet boundary conditions as mentioned above. The simulations were solved using the Implicit Unsteady Solver, due to the Segregated Flow model also being used. Turbulence was accounted for using the Realizable K epsilon model, which is the improved version of the standard K epsilon model, and includes a new transport equation for the turbulent dissipation rate epsilon [23]. The hull was fixed in all axis of rotation and translation, this meant that trim and sinkage effects were not included in the simulation. Convergence was measured by plots of the x and y forces and the z moments over time. Measurements were taken in the form of surface elevations and longitudinal wave cuts.

3.1.1 CFD VERIFICATION AND VALIDATION

The verification and validation of results are important parts of any study based on numerical methods. In this study, experimental testing was outside the scope of work due to the extent of time and resources it would require. Therefore, the experimental results were sourced from other projects. The validation of the CFD results was completed using experimental data for shallow water gathered from Macfarlane [6] and data extrapolated from experimental results for deep water from Macfarlane et al., [24]. These experimental results were gathered at the test basins in the Australian Maritime College (AMC) in Tasmania, Australia. The difference between the two data sets is that the experimental results from Macfarlane [6] are for a 24m catamaran in shallow water (h/L=0.55), while the results from Macfarlane et al., [24] are extrapolated from experimental data including the same 24m catamaran and a 30m catamaran in deep water.

Table 2: CFD Validation Hull Characteristics

HULLS	*h (m)*	*L (m)*	*V (kt)*	*Δ (t)*	Fr_h	Fr_L	*h/L*
Deep Water Data	*60*	*29.6*	*19*	*31*	*0.4*	*0.57*	*2.03*
Hull used in CFD Simulation	*60*	*29.6*	*19*	*28*	*0.4*	*0.57*	*2.03*
Shallow Water Data	*12*	*24*	*19*	*55*	*0.92*	*0.65*	*0.55*

Again, due to a lack of time and resources, it was impossible to replicate the experiments exactly in CFD. However, since the hull shapes tested by Macfarlane [6] and Macfarlane et al. [24] are of a similar shape and have similar characteristics it was decided that a comparison between the two would give a good indication of the validity of the CFD results. Comparing the two sets of results does show that the CFD results are within a similar range with only a small margin of error. These results were compared with the results of the preliminary hull.

To compare the wave heights and wave periods of the experimental results and the CFD results, wave-cuts were made using STAR CCM+ at the lateral distance from the sailing line of 41.4m (corresponding to the y/L ratio of 1.38 used in the experimental results of Macfarlane [6] and Macfarlane et al. [24]. These wave heights could then be compared with the wave heights and periods [6] and [24] for the corresponding Froude length number of 0.75. The results of the CFD validation are shown below in Table 3, where H_A, T_A, H_B, T_B are the wave heights and periods of waves A and B[2], respectively.

Table 3: CFD Validation Results

RESULTS	H_A *[mm]*	T_A *[s]*	H_B *[mm]*	T_B *[s]*
Wave Predictor 1	*171*	*5*	*289*	*4.5*
Hull used in CFD Simulation	*175*	*4.5*	*275*	*3.9*
Exp. Results of 24m cat at 10m/s	*250-450**	*5.75-6.5**	*550-850**	*3.5-4.75**
**Range of experimental results with error bars included*				

3.1.1 Preliminary Study CFD Results

The results gathered from the CFD simulation for the preliminary hull study included wave cuts and surface elevations. The wave cuts were used to accurately measure the wave heights and periods of the waves, while the surface plot allows the wave pattern and its features to be visualized. It can be seen in the surface plot, Figure 2, that the wake pattern shares the general form of the standard Kelvin wake pattern for sub critical flow, as expected.

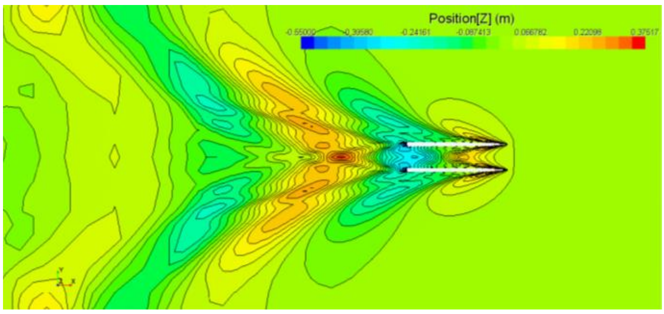

Figure 2: Preliminary Study CFD Simulation Results

As can be seen in Figure 2 the wake has multiple waves following in quick succession, this is because each hull has two main wave trains: one that propagates from the bow and one that propagates from the stern. The leading waves of a wake are described by Macfarlane [6] and Robbins [7] as two separate but equally important waves. The first wave (termed wave A) is characterized by a large period

[2] Wave A and B are defined in the following section.

and medium to high wave height. Adding these two characteristics together means that in many instances this first wave can have the largest total wave energy. The second wave, named wave B, is characterized by the highest wave height of the wave group following wave A and usually has a larger wave height but a lower period than wave A. In many situations this is the wave with the highest wave energy. Therefore, these waves are important to analyze, as they stand out because of their potential for damage in coastal areas due to their high wave energies.

3.2 Funwave

The Funwave code was used to simulate wave propagation from a pressure distribution moving along the water surface in a channel. The preliminary study was used as a proof of concept for calibrating the pressure distribution to replicate the wave heights found from the CFD simulation more accurately. The importance of being able to calibrate the pressure distribution becomes clear when you consider that the pressure distribution of Li & Sclavonous [17] only uses the Length, Breadth and Draft of the hull to describe the pressure distribution, as shown in Figure 3. Where the length and breadth describe the outer limits of the pressure distribution and the draft is used to calculate the maximum pressure value (Pm) used to model the pressure distribution. The maximum pressure value Pm, is the hydrostatic pressure given by Equation 4.

$$P_m = \rho \cdot g \cdot T \ [Pa] \tag{4}$$

Where ρ is the density of water, g is the gravity constant and T is the ships draft.

The maximum pressure value is then used to calculate the pressure distribution described by Li & Sclavonous [17], as shown in Equation 5.

$$P = -P_m \left\{ cos^2\left(\frac{\pi x}{L}\right) cos^2\left(\frac{\pi y}{B}\right) \right\} , -\frac{L}{2} < x < \frac{L}{2} , -\frac{B}{2} < y < \frac{B}{2} \tag{5}$$

Where P is the pressure distribution, L is the ship's length and B is the ship's beam.

The domain of the preliminary study used 901 grid points in the longitudinal direction and 301 points transversely. The dx and dy grid separations were both set to 1m, which yielded a length and breadth of 900m and 300m respectively. This grid separation was chosen because it gave good simulation stability and the long length of the domain allowed the results to be taken later in the propagation process, allowing the surface elevations to be fully developed. The Funwave input data is shown in Table 4.

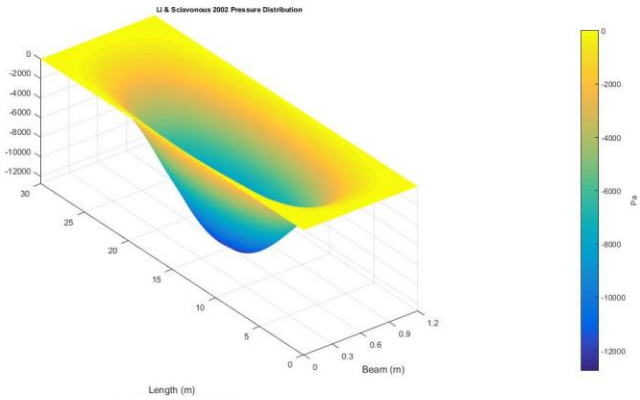

Figure 3: Pressure Distribution Used in Funwave Code

Table 4: Preliminary Study Funwave Input Data

Description	*Symbol*	*Value*
Longitudinal grid separation [m]	*dx*	*1*
Lateral grid separation [m]	*dy*	*1*
Time step [s]	*dt*	*0.03*
Water depths [m]	*h0*	*20*
Froude depth number [-]	*fh*	*0.7*
Ship Speed [m/s]	*vb*	*9.8*
Sponge layer width [grid points]	*ISPG*	*62*
Ship Length [m]	*L*	*30*
Ship Beam [m]	*B*	*1.2*

The Funwave code was run for several 'applied' ship drafts, although the hull's actual draft is 1.3m, so that the effect of the hull's shape can properly be accounted for. The drafts tested for the preliminary study ranged from 0.8 to 1.4 meters. The outputs for each simulation were read by MATLAB and surface elevations and wave-cuts were compared with the same outputs for the CFD simulations.

3.2.1 Funwave Calibration

In general, the Funwave results compared better with the CFD results the further laterally the wave-cut is measured. This is expected, as the CFD program can simulate the near field results with much higher accuracy than the Funwave code can. This is because the Funwave code was originally created to simulate wave propagation over very large distances, which it does very well, however it doesn't necessarily predict wave propagation as accurately in the near field. This is also why it is important to calibrate the Funwave code for the widest possible CFD results, because the CFD is still accurate in this mid field region and the Funwave code is as accurate as possible. It was found that the 'applied' draft of 1.4m gave the best agreement with the CFD results at the 45m wave-cut, as shown in Figure 4. Both the wave heights and wave periods are very similar, although there is a small gap in the phase of the two wave trains. This does not really matter, if the Funwave code is simulating the correct wave heights and wave periods, because if the wave heights and periods are correct, it will also accurately predict the wave energy. For this reason, it was chosen as the best approximation of the wake wash of the preliminary hull.

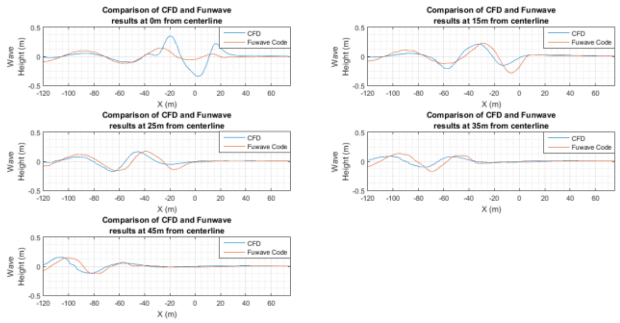

Figure 4: Preliminary Study Comparison of Wave-Cut Results at 0m, 15m, 25m, 35m and 45m for a 'applied' draft of 1.4m

4 MAIN STUDY

The main study focuses on the calibration of the Funwave code using the results of 8 CFD simulations in a channel.

4.1 CFD Simulations

The CFD simulations for the main study used a similar range of hull characteristics to the preliminary study so it was considered acceptable to use the same model, since the model was shown to be accurate and validated. The range of values used in the main study for the CFD simulations are summarized in Table 5 below. Measurements were taken at the lateral line 45m from the sailing line, inside the Near Field Region, and at the bow. The Near Field Region was defined as the space 1 ship length each side of the sailing line and from the stern to 2 ship lengths aft.

Table 5: Main Study Hull Characteristics

Characteristic	*Value(s)*
Length [m]	*30*
Beam [m]	*8 & 10*
Draft [m]	*1.3*
Demi Beam [m]	*1.5 & 2.5*
Half Bow Entry Angle [deg]	*14 & 24*
Bow Keel Rake [deg]	*0 & 50*
Vessel Speed [kt]	*25*

The results taken from these measurements are shown in Table 6 below. The wave heights are measured in meters and are measured from the height of the wave peak to the bottom of the next trough, except for at the bow where the height is just the surface elevation from the undisturbed free surface. The different combinations of hull characteristics have a significant impact on the wave heights in the near-field region and at the bow, however these effects become less apparent at the 45m lateral line. This is due to wave height attenuation and at a certain distance (in deep water) it would not matter which hull was chosen, as the waves heights would all be extremely similar. However, in congested waterways or where the bathymetry is varied, this type of data is very important for understanding what effects each characteristic has on the wave heights and wave energy.

Table 6: Main Study CFD Results

HULL	*Measurements taken at 45m*			*Near Field Region*	*At Bow*
	Max Wave Height [m]	*Period [s]*	*Energy [kJ/m/s]*	*Max Wave Height [m]*	*Max wave Height [m]*
1	*0.350*	*5.8*	*0.981*	*0.781*	*0.823*
2	*0.248*	*6.6*	*0.515*	*0.469*	*0.988*
3	*0.207*	*5.8*	*0.358*	*0.469*	*0.719*
4	*0.219*	*6.2*	*0.402*	*0.547*	*1.220*
5	*0.396*	*5.8*	*1.287*	*0.781*	*0.826*
6	*0.409*	*6*	*1.373*	*0.938*	*1.472*
7	*0.350*	*5.6*	*1.030*	*1.094*	*0.861*
8	*0.374*	*5.8*	*1.173*	*0.938*	*1.599*
AVG	*0.319*	*6.0*	*0.890*	*0.752*	*1.064*

4.2 Funwave Calibration

To calibrate the Funwave code for each hull, only the 45m lateral line was used, as mentioned above this measurement is the smartest choice because both the CFD and Funwave results are accurate in the region. The to aid the calibration process a code was created in the program MATLAB to compare the wave heights and periods from the CFD and Funwave programs together. This allowed the most accurate ‘applied’ draft for each hull to be selected, the results are tabulated for the CFD and Funwave (FW) wave heights and periods below.

Table 7: Main Study Funwave Calibration Results

Hull	*Beam [m]*	*Applied Draft [m]*	*Wave Height CFD [m]*	*Wave Height FW [m]*	*Wave Period CFD [s]*	*Wave Period FW [s]*
1	*1.50*	*1.60*	*0.35*	*0.32*	*5.80*	*4.28*
2	*1.50*	*1.15*	*0.25*	*0.23*	*6.60*	*4.67*
3	*1.50*	*1.00*	*0.21*	*0.20*	*5.80*	*4.67*
4	*1.50*	*1.05*	*0.22*	*0.21*	*6.20*	*4.67*
5	*2.50*	*1.80*	*0.40*	*0.37*	*5.80*	*4.67*
6	*2.50*	*1.75*	*0.41*	*0.35*	*6.00*	*4.67*
7	*2.50*	*1.60*	*0.35*	*0.32*	*5.60*	*4.28*
8	*2.50*	*1.70*	*0.37*	*0.34*	*5.80*	*4.27*

It is obvious from the data presented above that these minor changes in the hull characteristics results in significant differences in wave height. Since the main hull characteristics (length, beam draft) are the same, apart from the change in the overall beam, the Funwave program would not be able to simulate the differences in the wave heights and periods. This is the main advantage of this calibration method – that it allows these differences to be simulated.

5 SECONDARY STUDY

The Design of Experiments factorial methodology allows the investigator to take a small test sample and project the results over a larger range of test values, while highlighting the main and interacting effects. Due the large cost (time and hardware) associated with CFD simulations, the method of *factorial* *experimental design* was utilized. Differing from standard statistical investigation, which take completely random subjects, this method requires carefully chosen combinations so that not only the main effects of each factor, but also the effects of combinations of factors, can be seen. This method was used to choose the 8 hulls used in the Main Study. The 8 hulls all share the same main characteristics but the 4 factors: *Beam*, *Demi Hull Beam*, *Bow Entry Angle* and *Bow Keel Rake* were changed. The combinations used for the 8 hulls were chosen so that results could be analyzed using the DOE methodology. Each Factor has a high and low Level, this is the minimum requirement to be able to analyze the effect of each Factor.

For simplicity, each factor is given a letter and the high and low levels are represented by a 1 and -1, respectively. The factorial has a specific order such that every combination of factors A, B and C are tested. The value D is calculated by taking the product of the high/low values of A, B and C. To calculate the effect of a factor, the product of the corresponding high/low value ($+/-_i$) and result (H_i) for each hull is summed and divided by the number of Factors (4), as shown equation (6) below.

$$Effect = \frac{1}{4}\left(\left(\frac{+}{-}\right)_1 H_1 + \left(\frac{+}{-}\right)_2 H_2 + \left(\frac{+}{-}\right)_3 H_3 + \left(\frac{+}{-}\right)_4 H_4 + \left(\frac{+}{-}\right)_5 H_5 + \left(\frac{+}{-}\right)_6 H_6 + \left(\frac{+}{-}\right)_7 H_7 + \left(\frac{+}{-}\right)_8 H_8\right) \qquad (6)$$

The results of this analysis are shown in Table 8 and Table 9. To make the table easier to understand, the absolute values (ABS) were normalized by the average value for each output shown in the last row of Table 6 (indicated by a %). In Table 8 and Table 9, the larger the value in absolute terms, the larger the effect that factor had on the output. A positive value means that the trend is increasing, that is, an increase in the value of the hull characteristic will increase the output. Inversely, a negative value suggests that the opposite is true. The results highlight that of the 4 factors, *Demi Hull Beam* is the key factor in terms of reducing the wave heights that propagate from the catamaran. This is most likely because this factor strongly effects the displacement of each hull, which according to Macfarlane [6], is one of the crucial factors which affects wake wash. For the waves propagating into the far field, the *Bow Keel Rake* is also important. This is most likely because in this study this factor affects the waterline length, which has been linked to wake wash wave heights by Fox et al. [4]. In the Near Field Region, the Beam also has a significant effect and Bow Wave is most affected by the *Bow Entry Angle* and *Demi Hull Beam*.

Table 8: Secondary Study Main Effects

DOE ANALYSIS		*1/2 Entry Angle [°]*	*Bow Keel Rake [°]*	*Demi Beam [m]*	*Beam [m]*
		A	*B*	*C*	*D*
Hw 45m	*ABS*	*-0.014*	*-0.063*	*0.126*	*-0.026*
Hw NFR	*ABS*	*-0.059*	*0.020*	*0.371*	*-0.176*
Hw Bow	*ABS*	*0.513*	*0.072*	*0.252*	*-0.061*
Ew 45m	*ABS*	*-0.010*	*-0.242*	*0.429*	*-0.080*
Hw 45m	*%*	*-4%*	*-20%*	*40%*	*-8%*
Hw NFR	*%*	*-8%*	*3%*	*49%*	*-23%*
Hw Bow	*%*	*48%*	*7%*	*24%*	*-6%*
Ew 45m	*%*	*-2%*	*-39%*	*69%*	*-13%*

Table 9: Secondary Study Interacting Effects

DOE ANALYSIS		*2nd Order Interactions*		
		AB=CD	*AC=BD*	*AD=BC*
Hw 45m	*ABS*	*0.031*	*0.032*	*0.023*
Hw NFR	*ABS*	*0.020*	*0.059*	*0.137*
Hw Bow	*ABS*	*0.107*	*0.180*	*0.009*
Ew 45m	*ABS*	*0.094*	*0.116*	*0.038*
Hw 45m	*%*	*10%*	*10%*	*7%*
Hw NFR	*%*	*3%*	*8%*	*18%*
Hw Bow	*%*	*10%*	*17%*	*1%*
Ew 45m	*%*	*15%*	*19%*	*6%*

6 CONCLUSIONS

This study developed a novel methodology utilizing a commercial CFD software to calibrate the pressure distribution used in the extended Funwave code so that the wake wash, of similar yet distinct hull shapes, can be assessed over a given bathymetry. This will allow researchers the ability to study the wakes of different ships on a larger scale. Prior to this development, the pressure distribution used in a Funwave code was defined by a ships' Length, Beam and Draft. This means that two hulls with different hull shapes, but these same characteristics, could not be differentiated. This new method has many applications, such as optimization of hull shapes for a given journey, optimization of vessel speed or route for a given ship and bathymetry to reduce environmental impacts, as well as the study of the effect of different hull characteristics on the wake wash of a ship and its interaction with its surrounding environment.

The studies showed that by varying the ships' draft as an input variable into the Funwave program, the wave heights of the wake wash could be matched for each different hull. Since the Funwave program can accurately predict the wake patterns, which affects the wave periods, varying the draft (and therefore the pressure distribution) effectively allows calibration of the wave heights. These calibrated inputs can then be run for any given bathymetry by editing the depth section of the code.

This research also studied the effect of four different hull characteristics on the wake wash of a catamaran. These four characteristics were: *Beam*, *Demi Beam*, *Bow Entry Angle* and *Bow Keel Rake*. The results showed that of these four characteristics, Demi Beam was the most influential factor in affecting maximum wave height and wave energy. The results also showed that the Bow Keel Rake was influential. These results agree well with conclusions by Macfarlane et al. [24] and Fox et al. [4], who both suggest that the *Demi Beam* and the *Waterline Length* greatly affect the maximum wave height and wave energy of a ship's wake wash. Analysis of the interacting effects did not show that any particular interaction was of more importance. This could be due to the small number factor levels studied or the range. Although it makes sense that certain combinations of factors will inevitably create large constructive or deconstructive wave interactions, it is also most likely that the main effects of the hull characteristics will have the largest effect on wave height and wave energy overall. This theory is supported by the studies of Tarafder & Suzuki [18] and Nizam et al. [19] that both conclude that for higher Froude numbers and hull spacings the interference effects are less distinguishable.

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