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Design Aspects of Catamarans Operating at High Speed in Shallow Water

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This report is dedicated to,
my beloved mother and family

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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DESIGN ASPECTS OF CATAMARANS OPERATING AT HIGH SPEED IN SHALLOW WATER

by Mohamad Pauzi Abdul Ghani

The thesis describes the investigation into the design aspects of the high-speed displacement catamaran. This work is an extension of the existing database on the high-speed displacement hull form series namely the NPL series. The experimental test programme has been extended in the current research to investigate the influence of bulbous bows on the high-speed displacement catamaran performance in deep and shallow water conditions. Four bulbous bows have been developed by ranging bulbous bow's projecting length, between 1.25% to 6.25% of the length of waterline. These bulbous bows have been designed and faired to the parent hull, NPL5b or known as a Model 5b of the NPL Series, whilst the after body and the fore body from amidships to $0.3L_{pp}$ are kept unchanged. However, the cross section parameter has been fixed at value 0.303 i.e. the ratio of the bulbous bow cross section area at forward perpendicular to the midship section area. Measurements of total resistance, wash, trim and sinkage have been made up to a Froude number of unity in deep and shallow water. In addition to the calm water tests, these models were also tested in regular waves covering a wavelength to ship length ratio λ/L between 0.5 and 2.0 whilst the wave height was maintained at 0.030 m. Measurements of added resistance in waves, pitch, heave and wash cuts were made. Thin ship theory computer codes namely *wavel3d.for* and *wave3d3ss.for* have been used to validate the measured wash cuts.

It was found that the experimental and numerical investigations provide a better understanding of the basic physics of wash, resistance and seakeeping of high speed displacement catamarans fitted with bulbous bows operating in deep and shallow water.

The results of the systematic experimental investigation with respect to the influence of bulbous bows on wash, resistance and seakeeping provide invaluable information with a view to developing design guidance at the preliminary design phase and for validation purposes.

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Nomenclature

Symbols and abbreviations used

GKN	Towing Tank No. 3, GKN Westland Aerospace Ltd., Isle of Wight
$Lamont$	Lamont Tank, University of Southampton
NPL	National Physical Laboratory
$SIHE$	Towing Tank, Southampton Institute for Higher Education
$Demihull$	One of the hulls which make up the catamaran
AP	After Perpendicular
FP	Forward Perpendicular
L	Ship Length, m
B	Ship Breadth, m
T	Draught, m
D	Depth, m
h	Water depth, m
∇	Volume of displacement, m^3
$\triangle$	Mass displacement, kg
$S_\circ$	Static wetted surface area, m^2
s	Separation between catamaran demihull centrelines, m
C_B	Block Coefficient
C_P	Prismatic Coefficient
g	Gravity acceleration, $9.81m/s^2$
ρ	Density of water, $1000kg/m^3$ for FW and $1025kg/m^3$ for SW
u, v	Speed or velocity, m/s
F_n, F_{nl}	Length Froude Number $[v/\sqrt{gL}]$
F_{nh}	Depth Froude Number $[v/\sqrt{gh}]$
H_{max}	Maximum wash height, m
H_{nd}	Non-dimensional wash height
C_T	Coefficient of total resistance
C_W	Coefficient of wave-making resistance
C_F	Coefficient of frictional resistance
C_R	Coefficient of residuary resistance

C_V	Coefficient of viscous resistance, $C_T = C_T - (1+k)C_F$
$(1+k)$	Form factor
R_{AW}	Added resistance in waves, N
σ_{AW}	Non-dimensional added resistance in waves
λ	Wavelength, m
ζ_a	Wave amplitude, m
Z_a	Heave amplitude, m
θ_a	Wave slope
$\omega_e\sqrt{L/g}$	Non-dimensional frequency
$\frac{R}{\triangle}$	Specific Resistance

Chapter 1

Introduction

1.1 Background

The maritime industry is continuing to develop in response to new technology and customer demands. In 1998 the world's fast ferry market has been valued at approximately US $4.5billion of which there are approximately 700 of such vessels around the world. Stena, for example, recently paid around £65M for their latest new vessel [37].

In recent years fast ferries which are capable of speeds in excess of 40 knots in water depth less than 10m have been operational. As high-speed operations near sensitive shorelines increase, complaints from the public on extensive wave wake or wake wash from these fast vessels increase also. Although the leading waves in the wash are very small in terms of wave amplitude compared to storm waves, they have a very long period and build in height rapidly in shallow water at the shoreline thereby causing substantial surges on beaches as well as breaching sea walls at high tide. This wake wash is likely to have environmental effects such as shoreline erosion as well as endangering swimmers and small boats. During 1997, as a consequence of public concern, the Danish Maritime Authority (1997) issued a governmental order which requires that the high-speed craft operator/owner has to show evidence that the ship-generated waves do not exceed a prescribed wave height criterion in shallow water along the entire route. Similar criteria exist for other regions, such as the Puget Sound, Seattle, some navigable inland waterways in the Netherlands and the River Thames, UK [59]. There are other areas which are equally sensitive to damage such as the Paramatta River in Australia, the Solent (i.e. particularly the route between Southampton and Isle of Wight), Nantucket, the Mare Island Channel and the East Bay Estuary in San Francisco Bay.

Wake wash or normally known as wash results from ship-generated waves. There is a general awareness of the importance of ship-generated waves in design. However, until recently, ship-generated waves analysis has not been fully considered in design studies except as one of ship's resistance component resulting from the energy expended in generating a wave pattern. As the design spiral is the traditionally accepted way of representing the ship design process, wash was not considered to be a part. The main dimensions and form are clearly fixed by other considerations. One may think of wash as another spoke of the wheel because the elements of design which affect wash are also directly related to ship performance such as resistance, stability, seakeeping, deadweight capacity etc.

There is a misconception in the public that wake wash is directly proportional to speed i.e. the faster the boat is going, the more wake it makes and the more energy that it is putting into the water and the more that will wash up on the beach. This is true when dealing with large displacement hulls (tankers, bulk carriers, etc) but not with lightweight high speed ferries particularly multihulls [97]

A large number of papers on this subject have been published since the early nineteenth century. However, emphasis has generally been placed on the determination of a ship's resistance resulting from the energy expended in generating a wave pattern and not on the effect of these waves.

1.2 Problem Definition

1.2.1 Background

The wake wash generated from high-speed craft is an important issue for shipbuilders and ship operators in seeking more environmental-friendly designs. The wash from a passing ship can be regarded as a pollutant. Over the past years, complaints from marine environment authorities have increased.

In the United Kingdom, a ship's wake wash project has been to be completed by the middle of year 2003, by a consortium of universities and companies working on a project known as SWIM (Ships Wash Impact Management) project and funded by the EPSRC (Engineering and Physical Sciences Research Council). The three-year project will bring together studies of the generation, propagation and impact of high-speed ship's wash. The University of Southampton is part of the consortium, which involved a major role in one of the three work packages known as WP1-Wash Generation. A vast experimental work has been carried out at various model testing facilities such as at SIHE, GKN, Qinetic Haslar etc. The author has been involved in most of this experimental work.

1.3 Scope of the Present Work

The research area of high speed displacement craft is wide. Therefore the present study will mainly concentrate on the wash, resistance and seakeeping produced by the proven hull form, one of the NPL series. This hull form also has been slightly modified by incorporating cylindrical bulbous bows into it.

The main objectives of this research are,

- Model experiments to provide a better understanding of the basic physics of wash, resistance and seakeeping of high speed displacement catamaran fitted with bulbous bows operating in deep and shallow water.
- Further model experiments in regular waves to study the influence of bulbous bows and wave lengths on the added resistance, pitch, heave and wash.
- To compare the experimental results of wash cuts with thin ship theory.
- To provide potential ship designers with a useful data base of wash, resistance and seakeeping of high speed displacement catamaran fitted with bulbous bows.

1.4 Outline of the Thesis

Chapter 2 presents an overview of the previous reported research on wake wash for design. In particular it draws our attention to the limited availability of literature covering wake wash generated by high speed displacement craft. A description of the current wake wash research methodologies used, together with their important elements and characteristics are also given.

In Chapter 3, a description of the bulbous bow design for high speed displacement craft together with their important parameters and characteristics are presented. This chapter also describes the tank testing for monohull and catamaran configurations at the Lamont and SIHE tanks. The experimental results i.e. the effect of bulbous bows on the resistance components, sinkage and trim are presented. The effect of bulbous bows on waves wash are also given.

Chapter 4 describes the experimental work in regular waves at SIHE tank. In addition to total model resistance, heave and pitch, the wave cuts in waves are also recorded. The wash deduced from these wave cuts were compared to the wash obtained in calm water previously in Chapter 3. The effect of bulbous bows on resistance, heave, pitch and as well as wash are also described.

Considering the variation in water depth and ship speed, it is prudent to continue the experimental work mentioned in Chapters 3 and 4 into a shallow water condition as reported in Chapter 5.

Having recognised the need to supplement the experimental work with theoretical investigation, a computer program using thin ship theory has been used to compare the measured and calculated wave cuts as described in Chapter 6. This covers the experiments in three different establishments namely Lamont, SIHE and GKN towing tanks. The computer program also gives a theoretical values of wave pattern resistance coefficients. It should be noted that this wave pattern resistance coefficient, C_{wp} is only part of the wave-making resistance coefficient, C_w.

Finally, in Chapter 7, the research results are discussed, recommendation for future research are made and conclusions drawn. This presentation includes the bulbous bows ranking and design trade-off of Wash, Resistance and Seakeeping on high-speed displacement craft performance.

Chapter 2

The Wash of High-Speed Craft: State of the Art

2.1 Background

In order to develop an appropriate measure it is necessary to review the principal characteristics of the well-established wave pattern which is generated by a ship in deep water. As a ship moves through the surface of a body of water, a wave pattern consisting of divergent and transverse waves is generated. Diverging waves are created at the bow and stern and will generally remain separated throughout their travel. Transverse waves also created at the bow and stern will, however, combine to form a single series of waves. Kelvin (1887) found that, for any deep water speed, the diverging and transverse waves form a constant pattern and meet to form a locus of cusps whose angle with the sailing line is $19°28''$. This cusps locus angle varies for real ships. For example for thin ships the cusps locus angle is lower at higher speeds. The cusps locus line also often intersects with the sailing line at a point ahead of the ship's bow [90]. A typical Kelvin wave pattern is shown in Figure 2.1. Kelvin's theory also predicts that the transverse and diverging waves meet at a common tangent that forms an angle of $54°44''$ with the sailing line of the disturbance. Lord Kelvin analytically investigated the wave pattern generated by a single point disturbance moving across the surface of deep water and generating groups of waves that move forward with directions of travel that vary continuously between $\pm 90°$ of the direction of travel of the disturbance (i.e. sailing line).

Havelock extended the work of Kelvin to show that the wave height at the cusp points decrease at a rate inversely proportional to the cube root of the distance from the disturbance, while the transverse wave heights along the sailing line decrease at a rate inversely proportional to the square root of the distance from the distance. Clearly any wash generated will gradually die out as it travels into the distance. Thus, at greater distances from the ship, the diverging waves become more prominent than the transverse waves.

The transverse waves celerity is equal to the ship speed. Thus, using linear wave theory, their length and period can be calculated for a given ship speed and water depth. The divergent waves have a celerity less than the ship speed and equal to $V \cos\theta$ where V is the ship speed and θ is equal to $54°44''$(maximum) given by Kelvin as described in previous paragraph. Consequently all the wash components radiate out in lines from the ship in a delta like formation. The longer faster waves are on the outside of the wash and have larger values of θ compared to the slower shorter waves with crests swept further back.

In general, a significant number of papers on the study of wake wash from high-speed craft were published during the 1990's.

Gadd (1994)[34] presented an approximate theoretical prediction method to predict the characteristics of high-speed boat wash by calculating the waves resulting from a distribution of surface pressure. It was treated as varying only in the longitudinal direction x axis over a rectangle whose length is the boat length L and whose width B is such that the area BL is equal to the water plane area of the boat. This prediction method is limited to high-speed hull forms with transom sterns whose immersed areas when at rest are a significant proportion of the maximum cross section. Gadd (1999)[35] proposed an Egger type analysis to deduce far field waves from model tests in a limited width of towing tank where the measurement of waves sufficiently far from the track is not possible.

Whittaker et al (1999)[109] carried out an investigation of the wash of high-speed ferries operating in Belfast Lough. The objective was to gain a better understanding of the physical processes of the wash, which aimed at producing a standardised methodology for assessing the environmental impact of high-speed ferry operating in coastal region. Several approaches and steps were employed to investigate wash effect in order to compliment or to cross check between them.

- An ultra-sonic measuring system mounted on fixed structure was used to monitor the elevation of the water surface. 150 wash time traces were recorded for the two fast ferries.
- A series of physical model testing.
- Computer modelling by using CFD which modelling of the ship water interaction using Shipflow.
- The wave transformation program, MIKE 21 developed by DHI was used to model how the wash waves are transformed by the seabed topography as they travel from the line of generation along the track of the vessel to the shoreline.

The wash produced by high speed displacement craft is classified in terms of depth Froude number as suggested by Havelock(1908)[42] such as,

- Sub-Critical Wash. $F_{nh} < 1$
- Critical Wash. $F_{nh} = 1$.
- Super-Critical. $F_{nh} > 1$.

Similar work was also reported by Henrik Konfed-Hansen(1999)[59] on investigation of wave pattern or wake wash from high-speed craft in Danish waters by field measurements, model experiments and numerical wave modelling. A description is also given of the phenomena and application of an efficient numerical model to describe wave propagation and transformation from the ferry route to the nearby coast. The model also includes the effects of refraction and shoaling due to varying depth. The DHI's MIKE 21NSW (Near-shore Spectra Wave model) is used for that purpose. The basic equations in MIKE 21 NSW were derived from the conservation equation for the spectral wave action density based on an approach proposed by Holthuijsen et al (1989)[47]. The model includes the effects of refraction and shoaling due to varying depth, wave generation due to wind, and energy dissipation due to bottom friction, wave breaking and also the effects of ambient current. The output of this model basically consists of wave height, wave period and wave directions. For a ship moving steadily in water of uniform finite depth, the nature of the wash which it creates will closely depend upon two non-dimensionless parameters; the length-based Froude number $F_{nl} = \frac{V_s}{\sqrt{gL_w}}$ and the depth-based Froude number $F_{nh} = \frac{V_s}{\sqrt{gh}}$.

In Henrik Konfed-Hansen's work (1998)[58], the results and analysis of full-scale wake wash measurements from a few Danish ferry routes were presented. These measurements have been supplemented by wave propagation modelling to develop methods which predict the areas of particular concern. These prediction methods are required in the planning of new ferry routes. A wake wash criterion, $H_h \leq 0.5\sqrt{\frac{4.5}{T_h}}$ where H_h is the maximum wave height of the long-periodic waves having mean wave period of T_h seconds was introduced. These criteria are applicable at a still water depth of 3 m.

In the sub-critical speed range ($F_{nh} < 0.6 - 0.7$) the wave system consists of diverging and transverse waves in a restricted wedge-shaped Kelvin wake, where the cusps are about $19°28''$ and almost independent of the ship speed [60] [77]. In this speed range, the wave period of the diverging waves is proportional to the ship speed $T \approx 0.27V_s$, where V_s in knots. For depth-Froude numbers beyond one (supercritical speed range), the transverse waves disappear and the wave system is characterised by a Havelock-like wave pattern i.e taken a convex form. This is typical for high-speed craft operating in coastal waters. The divergent waves are now contained within an angle which depends on the speed of the ship. In the transcritical speed range ($F_{nh} \approx 0.9 - 1.1$), transverse and divergent waves merge together into wave fronts which are almost nearly straight and perpendicular to the ship's track. High amplitude waves are typically generated at these speeds. Wake wash generated by high-speed craft is markedly different to waves from conventional ships. Wave measuring programs have demonstrated that the high-speed craft generates diverging wave pattern consisting of groups of long period waves and short periodic waves. The long waves from large carrying fast ferries normally have more than 9 seconds wave period. These waves have a relatively larger wave height growth during shoaling and wave refraction which is caused by seabed irregularities in deeper waters. The result is that the waves when reaching the shore consist of higher breaking waves and have a larger run-up than traditional ship waves and the breakers have more of a plunging effect. The waves will arrive faster than ordinary Kelvin waves and particularly during calm weather conditions, people on the beach will not be prepared for a breaking wave appearing without any warning. This is a main reason for the public concern over wake wash from high-speed craft [58]. The work of Taatø et al (1998)[98] concluded that the propulsion system on large high-speed craft (water jets) may cause increased wave heights of 20-40% compared to the bare hull.

The correlation between hull characteristics such as length of waterline L_{LWL} and length to beam ratio $\frac{L}{B}$ to the wash characteristics has been carried out by Stumbo [95] and Dand [17]. This was achieved by measuring the wake wash characteristics of numerous aluminum catamarans of various displacements, lengths and hull forms. A submerged pressure sensor was used to record wave height and wave period and with these two components, wash height and wash energy density can be determined for various ship speeds. An assumption is made that in deep water, after a wave travels a certain distance from the point of generation, gravity will cause the wave to assume a sinusoidal wave profile and then linear wave theory can be applied. Based on this assumption, the author had used classic wave theory to quantify and characterize the wash produced by various hull forms. It is suggested that a design goal of low wake wash could be achieved by designing a vessel which achieves hump speed as early as possible with the lowest possible hump wash height and energy density. From the graph produced it was shown that the hump speed varied proportionally with the length L_{LWL} and the wash height and energy density at hump speed were inversely proportional to the length to beam ratio, $\frac{L_{LWL}}{B}$. It was concluded that water line length and length-to-beam ratio were very important parameters in the design of low wash ships. In a successive paper [97], he presented the wash prediction by computational fluid dynamics using a nonlinear free surface module, FSWAVE coupled to a three-dimensional panel method, VSAERO. VSAERO/FSWAVE can be thought of as combined Green's Theorem/Velocity Method approach to a panel method, where Green's Theorem is applied to solid bodies and Velocity Method is used on the free surface. He also introduced criteria of acceptable wake wash for Washington

State Ferries. The no harm level was established at

- Wash height of 28 cm, measured 300 m from sailing line.
- Wash energy density of 2450 joules/m in the highest significant wave of the wave train as measured 300 m from sailing line.

as shown in Figure 2.2 and Figure 2.3 respectively.

Bertram (1999)[3] discussed the utilization of nonlinear wave resistance codes to predict wash generated by high-speed craft. The codes involved were VSAERO, FSWAVE and SHALLO which are very similar and representative for a widely used class of boundary element codes (commonly known as panel codes). From his computer prediction and full-scale measurement results analysis, he concluded that wash depends on the size and shape of the ship, speed, water depth and a distance to shore. The main design parameters are the hull slenderness and the displacement. Long slender lightweight hulls with fine entrance, rounded bottoms, and smooth transition to the stern profile are likely to produce low wash characteristics. However, the characteristics that produce low wash might not be those that produce favourable seakeeping characteristics, good space utilization, or high transport efficiency. It was concluded that the numerical wash prediction could predict with sufficient accuracy the wash near the ship and in rectangular channels with rigid walls for the subcritical and supercritical speed.

The full-scale measurement or a field study approach to the wake wash generated by by high speed ferries problem has been carried out by Hannon, et al (1999)[41]. This field study was carried out on site at Loch Ryan where Stena Line operates their HSS1500, Lynx wave-piercing catamaran and Ro-Ro ferries, SeaCat Scotland utilizes a wave-piercing catamaran while P&O operates a Jetliner planing monohull and two Ro-Ro ferries. This was solely a field measurement works and the result very much depended on the recorded wave elevation time history.

It is accepted practice to obtain a time history for the longitudinal cut of wave elevation as a ship passes a wave measurement devices as described by Sorensen, [90][91]. These time histories can be obtained, from either model or full-scale experiments, through the use of common measurement tools such as capacitance or resistance wave probes, submerged pressure transducers and wave rider buoys. Measurements such as significant wave height and a wave energy may well be more representative of the distribution of wave heights and periods within any given ship-generated wave pattern than maximum wave height as proposed by Sorensen, et al[92][94]. Sorensen(1973)[93] recorded a height of ship-generated waves produced by different types of ship at 100 feet, 500 feet and 1000 feet from sailing line as shown in Table 2.1. This data has also been plotted in Figure 2.4 and Figure 2.5.

These figures show the influence of depth Froude number, length Froude number and distance from sailing line on the wash height and their decay rate.

Vessel Type	**L** m	**B** m	**T**	**DISPL** tonnes	**d** m	**V** knots	**H100** m	**H500** m	**H1000** m
Cabin Cruiser	7	2.5	0.5	2.722	12.2	6	0.2	0.1	
						10	0.4	0.2	
Coast Guard	12.2	3	1.1	9.072	11.6	6	0.2	0.3	
Cutter						10	0.5		
						14	0.7		
Tugboat	13.7	4	1.8	26.3	11.3	6	0.2	0.1	
						10	0.5	0.3	
Rescued Craft	19.5	3.9	3	31.8	12.2	6	0.1		
						10	0.4	0.2	
						14	0.6	0.3	
Fireboat	30.5	8.5	3.4	311.2	11.9	6	0.1	0.06	
						10	0.5	0.3	
						14	0.9	0.8	
Barge	80.2	16.8	4.3	4917	12.8	10	0.4	0.2	0.1
Tanker	153.6	20.1	8.5	17100	17.1	14		0.5	0.3
						18		1.6	1.4

Table 2.1: Data of ship-generated waves[92]

Based on the model tests results Khattab (1999)[57] found that the wash amplitude was proportional to the cube of boat speed. He also concluded from his various model tests that the generated wash depends on Froude number, slenderness ratio, half-angle of entrance, bow section shape, waterline shape, stern shape, forward prismatic coefficient and position of longitudinal centre of buoyancy.

Macfarlane and Renilson (1999)[69] listed the parameters which should be considered when dealing with ship-generated waves prior to conducting the experiment and/or reporting wave wake results. They discussed this at length in their paper.

The most accurate way of obtaining wake wash or ship-generated waves is by means of experiment, either on full-scale or with models. However it would sometimes be useful to make approximate theoretical predictions of the waves in the preliminary stage to judge the suitability and acceptability of the boat. The use of CFD codes to model these phenomena has its own limitations. They do not permit calculations of the far field wave pattern and more often the calculation is limited to an area within three to five ship lengths.