# An Experimental Investigation into Wash Wave and Resistance of High Speed Displacement Craft in Shallow Water

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## Abstract

The paper summarises resistance and wash wave measurements on a series of high speed displacement monohull and catamaran forms in shallow water. Experimental tests on models of high speed craft have been carried out in shallow water. The models used were of round bilge form with transom sterns derived from the NPL and the Series 64 round bilge series. Longitudinal wave cuts, model resistance, sinkage and trim were measured. The effects of length to displacement ratio ($L/\nabla^{1/3}$), catamaran demihull separation to length ratio (S/L), speed, transom immersion, shallow water and propulsion systems on wave wash and resistance were investigated. The data are very useful for low wash designs and for the validation of theoretical wash prediction methods.

## 1. Introduction

The use of high speed displacement craft, both monohull and catamaran forms, has been increased which has led to a new range of problems. With the arrival of higher speeds, shallow water effects tend to have an earlier influence and can have a significant effect on the generation of the ship near field wave system and wave pattern resistance. This in turn influences the resistance and hence powering of the ship. The waves generated by such craft can impact upon safety and the environment in terms of the safety of smaller craft, people on beaches, coastal erosion and changes in the local ecology.

Extensive research into the resistance components of high speed displacement monohulls and catamarans has been carried out at the University of Southampton over a number of years, [1 - 4]. However, the tests were concerned mainly with the performance of the vessels in deep water. There is limited published information on tests in shallow water, such as those reported in Ref. 5 - 6. Therefore, a series of experiments have been carried out in shallow water to enhance the understanding of shallow water effects and are presented in this paper.

The earlier model tests in deep water were carried out in the Towing Tank at Southampton Institute whilst the tests in shallow water were carried out at the GKN Westland tank on the Isle of Wight. Longitudinal wave cuts, model total resistance, sinkage and trim were measured. The tests also covered a range of catamaran demihull separation to length ratios (S/L), two shallow water depths and significant bow and stern trim. These allowed the effects of separation to length ratio, water depth and trim changes or transom immersion on total resistance and wave wash to be investigated.

Two separate model 5s catamarans, one self-propelled by propellers and the other by water jets, were tested in shallow water in order to investigate the effect of propulsion systems on the generation of wave wash.

## 2. Description of Models

A total of four hull forms were tested. Details of the models used are given in Table 1 and their body plans are shown in Fig.1. The models were constructed using an epoxy-foam sandwich skin.

The models were of round bilge form with transom sterns and were derived from the NPL round bilge series [7], designated model 4b, 5b and 6b and the Series 64 round bilge series [8], designated model 5s. The models were tested as monohull and catamaran configurations with separation to length ratios (S/L) of 0.2, 0.3, 0.4, and 0.5.

The model towing force was in the horizontal direction. The towing point in all cases was situated at the longitudinal centre of gravity and at a height of 1.5 times the draught above the baseline. The models were fitted with turbulence stimulation comprising trip studs of 3.2mm diameter and 2.5mm height at a spacing of 25mm. The studs were situated 37.5mm aft of the bow. No underwater appendages were attached to the towed models.

Model 5s in catamaran configuration was also tested in self-propelled form. The 1.6m model was propelled either by two propellers or four waterjets and powered by DC electric motor.

## 3. Facilities and Tests

### 3.1 Towed Model Experiments

The shallow water experiments were carried out in the GKN-Westland Aerospace test tank on the Isle of Wight, which has principal particulars as follows:

| | | |
|---|---|---|
| Length | : | 200m |
| Breadth | : | 4.6m |
| Water Depth (deep water) | : | 1.7m |
| Maximum Carriage Speed | : | 14m/s |

In the current tests, water depths of 200mm and 400mm were used.

The deep water experiments were carried out on the 1.6m model in the Southampton Institute towing tank. The tank has the following principal particulars:

| | | |
|---|---|---|
| Length | : | 60.0m |
| Breadth | : | 3.7m |
| Water Depth | : | 1.85m |
| Maximum Carriage Speed | : | 4.6m/s |

Both tanks have a manned carriage which is equipped with a dynamometer for measuring total resistance together with various computer and instrumentation facilities for automated data acquisition.

Total resistance, running trim, sinkage and wave elevation were measured in calm water. The tests were carried out over a speed range up to length Froude Number ($Fn=V/(gL)^{1/2}$) of 1.0 for deep water cases and the shallow water tests were carried out at a speed range of 1m/s – 4m/s corresponding to a length Froude Number range of 0.2 to 1.0 and a depth Froude Number ($Fn_H=V/(gH)^{1/2}$) range of 0.2 to 2.8. L is length of the model at waterline and H is water depth.

### 3.2 Self-propelled Model Experiments

For the self-propelled tests in shallow water, 1.6m models 5s were carried out in the GKN-Westland Aerospace test tank. The tank is equipped with instrumentation to measure the speed of the carriage. The speed controller for the waterjets and propellers, together with a 60 Ah 12v battery and charger were situated on the carriage to reduce the weight in the model. Two aluminium guide posts ran in an aluminium frame beneath the main carriage. For each test run the model was run up to the set carriage speed.

### 3.3 Wave pattern measurement

The wave profiles were measured using resistance type wave probes with a length of 300mm coupled to Churchill wave probe monitors. The data were acquired and stored using a laptop computer.

During each test run of 1.6m model 5s in deep water at the Southampton Institute towing tank, four longitudinal wave profiles were measured, with transverse position (Y) relative to the tank centreline to the model length ratios (Y/L) of 0.694, 0.77, 0.86, and 1.028. The longitudinal position of the wave probes was about halfway down the tank which allowed adequate time for the wave system to settle before measurements commenced.

For the shallow water tests, models 4b, 5b, 6b, and 5s were used and tested at GKN-Westland Aerospace test tank. Seven longitudinal wave profiles were measured at the transverse position to model length ratios (Y/L) of 0.43, 0.55, 0.68, 0.80, 0.93, 1.05, and 1.18 for models 4b, 5b, and 5s and Y/L of 0.33, 0.42, 0.52, 0.61, 0.71, 0.80, and 0.90 for model 6b. The longitudinal position of the probes was about the middle of the tank.

## 4. Data Reduction and Corrections

The resistance data were reduced to coefficient form using fresh water density ($\rho$=1000 kg/m$^3$), model speed (V) and static wetted surface area (A). It is noted that in the case of the catamarans the sum of the wetted surface areas of both demihulls was used.

$$\text{Resistance Coefficient} = \text{Resistance}/(0.5\rho AV^2) \qquad (1)$$

The total resistance measurements were corrected to the standard temperature of 15$^{\circ}$C. Blockage effects due to tank breadth were found to be small.

## 5. Presentation of Data

The residuary resistance coefficient $C_R$, rather than total resistance coefficient $C_T$, is used for the presentation of experimental resistance data as the residuary resistance consists mainly of wave resistance. It is obtained from $C_T$ =

$C_F + C_R$. Where $C_T$ is total resistance coefficient measured from the tests, $C_R$ is residuary resistance coefficient and $C_F$ is frictional resistance coefficient calculated from ITTC $C_F = 0.075/[\log (Rn)-2]^2$.

The wave profiles are presented in terms of wave height (m) to a base of longitudinal distance, X (m) for a given model or ship speed. The running trim was presented in degrees and taken positive for bow up. The sinkage was taken positive for vertical movement downward and non-dimensionalised using the draught of the model.

For the investigation of shallow water effects, the depth Froude number is used and defined as $Fn_H = V/(g.H)^{0.5}$ where H is water depth in meters. The wave wash is defined as sub-critical, critical or supercritical as $Fn_H <, =, \text{or} > 1.0$ respectively.

The data are presented in Figs. 2 - 20 in terms of the influence of $L/\nabla^{1/3}$, S/L, shallow water and trim changes on the residuary resistance and the wave characteristics.

## 6. Discussion of Results

### 6.1 Residuary Resistance

The effect of length to displacement ratio ($L/\nabla^{1/3}$) on residuary resistance is illustrated in Fig.2. As the length to displacement ratio ($L/\nabla^{1/3}$) increases (moving from model 4b to 6b), the residuary resistance coefficient decreases, especially at the hump. A similar trend was also obtained in deep water by Molland [3].

Figs.3 - 5 show the influence of S/L. The residuary resistance coefficients of the catamarans are greater than that of monohull, especially at the Fn between 0.4 and 0.6. This is due to the interference effects between the demihulls. It is noted that $C_{Rcat} = R_{Rcat}/(0.5\rho AU^2)$ where A is the wetted surface area of both demihulls. For catamarans, the general trend is that as the hull separation reduces, the residuary resistance increases. The effect is significant at the hump i.e. Fn between 0.4 and 0.6 for the deep water case. In the higher speed range, changes in hull separation tend to have a relatively small effect. The trend is also the same as that of models 3, 4 and 6 which have different length to breadth ratios (L/B) and breadth to draught ratios, see Ref. 3.

It is also seen from Figures 3 and 5 that the resistance coefficients of model 5b and 5s which have the same $L/\nabla^{1/3}$ but different hull shape are hardly different. With regard to the effect of speed, as the speed increases the residuary resistance coefficient gradually increases and peaks at a Froude number of about 0.45 and then decreases.

Figs.6 - 7 show the curves of resistance ratio ($R_R/R_{R\infty Depth}$) against depth Froude number, $Fn_H$. It is clearly seen that the shallow water effect on the resistance is significant around the critical depth speed region ($Fn_H \cong 1.0$). This increase is larger for the smaller water depth (0.2m). This is likely to be due to the smaller clearance under the keel for the smaller water depth leading to larger interference. At sub-critical and supercritical speeds the resistance values are very similar and effectively independent of water depth. Similar results were obtained by Dand [5] and Millward [9, 10].

There is a distinct increase in running trim as the speed passes through the critical depth speed region, as seen in Fig.8. These increases were found to be considerably higher than for deep water. Furthermore, as the speed approaches critical $Fn_H$, the vessel firstly arises then sinks significantly through the critical region before rising again at higher speeds, Fig.9. The significant running sinkage might be an important operational consideration if keel to ground clearances become small.

As seen in Fig.10, bow up trim causes an increase in residuary resistance coefficient at around critical depth speed (Fn = 0.35 in this case).

### 6.2 Wave Wash

It is seen from Figs.11 – 13 that the effect of length to displacement ratio ($L/\nabla^{1/3}$) on the wave profiles is similar to the effect on the resistance, namely, an increase in length to displacement ratio ($L/\nabla^{1/3}$) (from model 4b to 6b) results in a reduction of the wave height. The wave phases of model 4b and 5b are almost identical whilst model 6b has shorter wavelength. It is noted that models 5b and 6b are compared at the same speed but not the same Fn as model 6b has a longer length. As shown in Fig.14, the wave profiles of models 5b and 5s are almost identical. This also agrees with the residuary resistance measurement.

It can be seen from Fig.15 that the effect of hull separation ratio on the generated wave is small although there is an increase in resistance as the hull separation is reduced, noting that the wave resistance is proportional to the square of wave amplitude $A_W^2$.

Figs.16 - 17 show the plots of wave height and half wave period of leading wave height against depth Froude number. Trends are similar to the residuary resistance results. There is a significant increase in wave height through the critical depth speed region. The effects seem to be a little less for the smaller 200mm water depth. At higher speeds beyond critical, the wave heights are broadly similar. The trend is similar for the half wave period of the leading wave.

Fig.18 presents the influence of the propulsion systems: water jets and propellers on the wave profiles in shallow water. The experimental wave cuts of model 5s catamaran with S/L of 0.4 traveling in shallow water are compared at supercritical speeds. It is seen in Fig.18 that the differences in wave elevation between the three propulsion methods are small. These are highly significant results as they imply that the towed case provides realistic wave cuts and wave heights which compare well with those from propelled models. This further implies that towed data can be used with some confidence for design and validation work.

Typical sub-critical and supercritical wave patterns are shown in Fig.19. Experimental measurements of the divergent wave angle of the leading wave, together with theoretical predictions [11], are shown in Fig.20. At sub-critical speeds, the wave angle is about $35^{\circ}$. As speed is increased through the critical region, the wave becomes almost perpendicular to the track of the craft before moving back to about $50^{\circ}$ to $60^{\circ}$ in the supercritical region.

More details and results of the investigation are presented in Ref.[12, 13]

## 7. Conclusions

7.1 The results of the investigation provide a better understanding of the resistance and wave wash of high speed displacement craft in shallow water.

7.2 The results show that an increase in length to displacement ratios causes a decrease in residuary resistance and wave height.

7.3 For catamarans, the hull separation to length ratio (S/L) was found to have an influence on resistance, especially at the hump speed. It hardly affects the wave wash.

7.4 Significant changes in model behaviour occurred at or near the critical depth speed, $Fn_H$=1.0. There are large increases in resistance and wave height and the direction of wave propagation becomes almost perpendicular to the track of the craft.

7.5 At around the critical depth speed, the resistance increases as the water depth is decreased. This implies that the shallow water effect at the critical depth speed depends on the water depth. This may be due to the effect of clearance under the keel.

7.6 Investigations using different methods to propel the models (towing, conventional propellers or waterjets) indicated that the propulsion method had only a very small effect on the wave height and patterns.

7.7 The data should prove useful for design and wave wash applications and for the validation of theoretical wash prediction methods.

## 8. Acknowledgements

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| Model | 4b | 5b | 6b | 5s |
|---|---|---|---|---|
| L [m] | 1.6 | 1.6 | 2.1 | 1.6 |
| $L/\nabla^{1/3}$ | 7.4 | 8.5 | 9.5 | 8.5 |
| L/B | 9.0 | 11.0 | 13.1 | 12.8 |
| B/T | 2.0 | 2.0 | 2.0 | 2.0 |
| $C_B$ | 0.397 | 0.397 | 0.397 | 0.537 |
| $C_P$ | 0.693 | 0.693 | 0.693 | 0.633 |
| $C_M$ | 0.565 | 0.565 | 0.565 | 0.848 |
| A [$m^2$] | 0.338 | 0.276 | 0.401 | 0.261 |
| LCB [%] | -6.4 | -6.4 | -6.4 | -6.4 |

Table 1: Principal particulars of models

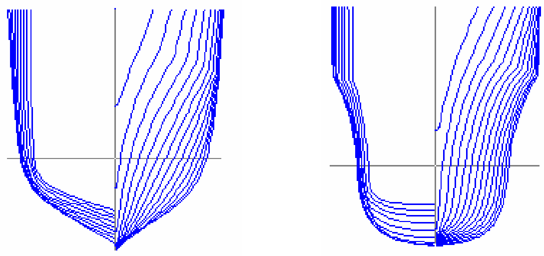


Fig.1 Hull Bodyplans

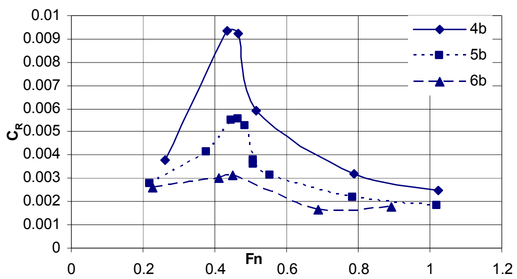


Fig.2 Residuary resistance coefficients (monohull, H=0.4m)

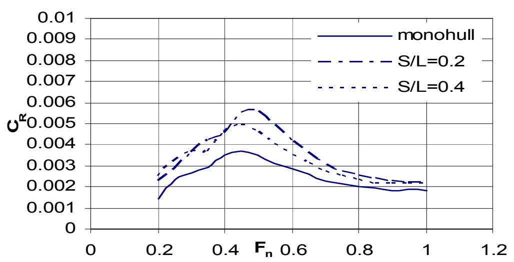


Fig.3 Residuary resistance coefficients (5b H=1.85m)

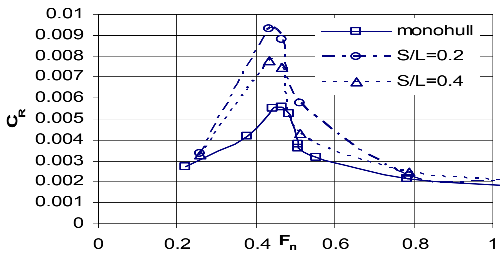


Fig.4 Residuary resistance coefficients (5b H=0.4m)

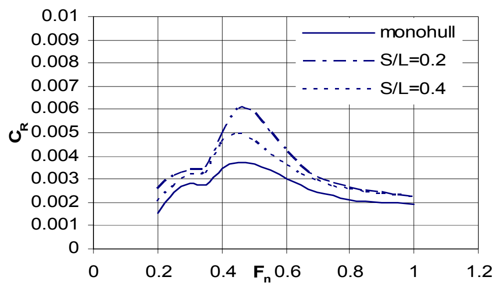


Fig.5 Residuary resistance coefficient (5S H=1.85m)

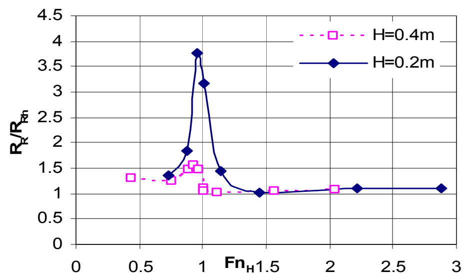


Fig.6 Resistance Ratio (5b monohull)

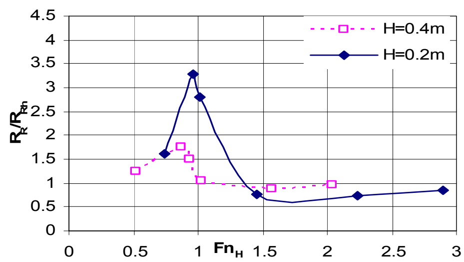


Fig.7 Resistance Ratio (5b catamaran S/L=0.2)

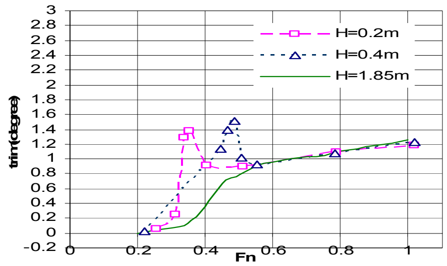


Fig.8 Running Trim (5b monohull)

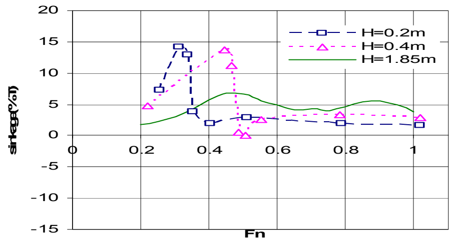


Fig.9 Running Sinkage (5b monohull)

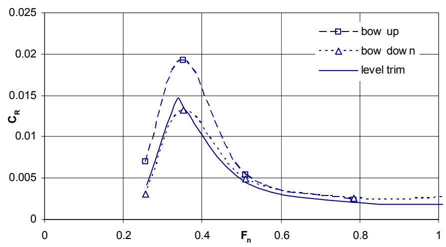


Fig.10 Residuary resistance coefficients (5S catamaran S/L=0.2 H=0.2m)

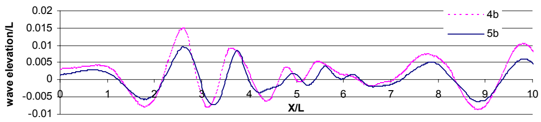


Fig.11 Measured wave cuts (monohull H=0.4m Fn=0.785 Y/L=0.55)

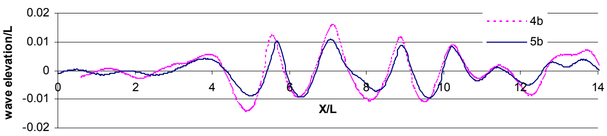


Fig.12 Measured wave cuts (catamaran S/L=0.4 H=0.4m Fn=1.0 Y/L=0.55)

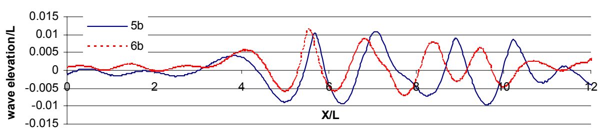


Fig.13 Measured wave cuts (catamaran S/L=0.4 H=0.4m Fn=1.0 / 0.88 Y/L=0.55 / 0.52)

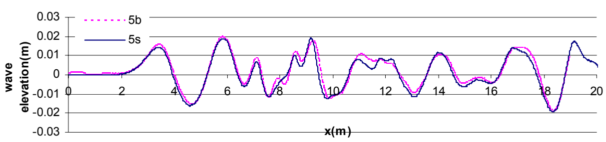


Fig.14 Comparison of wave cuts: catamaran S/L=0.2 Fn=0.5 $Fn_H$=1.43 H=0.2m Y/L=0.68

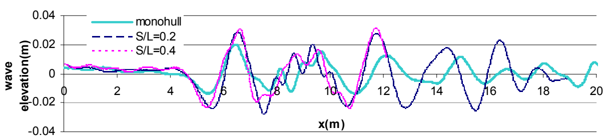


Fig.15 Measured wave cuts (5b H=0.4m Fn=0.44 $Fn_H$=0.88 Y/L=0.55)

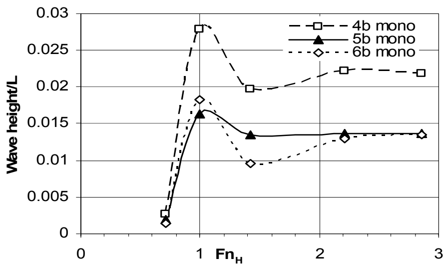


Fig.16 Leading wave height (H=0.2m)

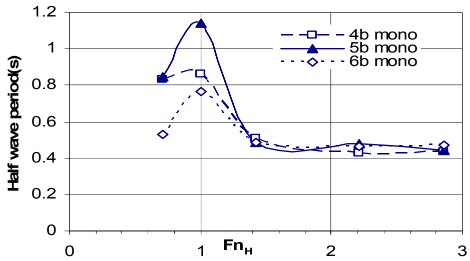


Fig.17 Half wave period of leading wave, H=0.2m

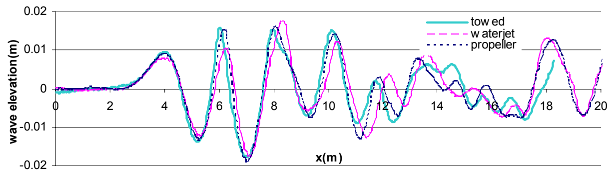


Fig.18 Comparison of wave cuts: 5s S/L=0.4 Fn=0.785 $Fn_H$=2.21 H=0.2m Y/L=0.55

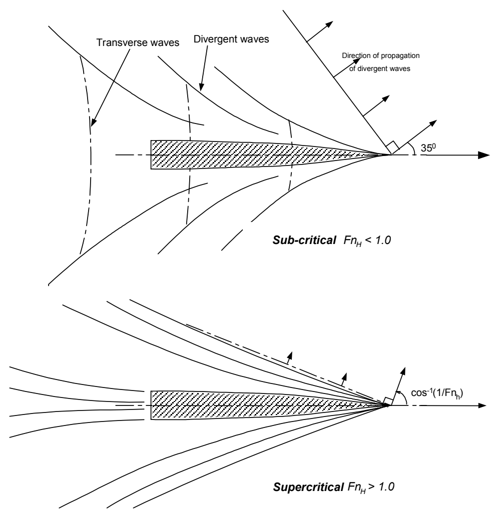


Fig.19 Sub-critical and supercritical wave patterns

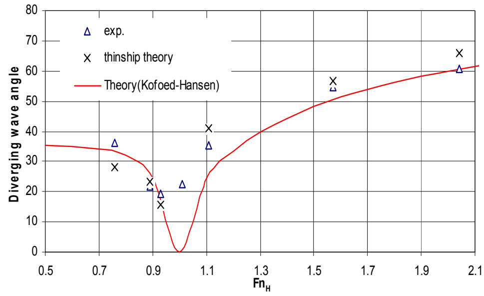


Fig.20 Diverging wave angle