Optimisation of the Catamaran Hull to Minimise of Motions and Maximise Operability

Edward Dudson, Ship Design Director, Nigel Gee and Associates Ltd, UK
Han Jorgen Rambech, Marintek Sintef Gruppen, Norway

SUMMARY

This paper describes the design and tank testing of a new fast catamaran vessel designed for the United States Navy Office of Naval Research for use as a Littoral Surface Craft. The Office of Naval Research have now ordered a demonstrator vessel named X-Craft currently under construction at Nichols Bros Boatbuilders Inc. A two year development programme at NGA produced a new hull form, the ModCAT, which when coupled with a powerful motion damping system met all of the US Navy Office of Naval Research requirements. Initial numerical studies predicted very low motions and speed loss. To validate the prediction an extensive programme of tank tests was undertaken in the ocean basin at Marintek, Trondheim.

AUTHORS' BIOGRAPHIES

Ed Dudson graduated from the University of Southampton in 1990 and joined Nigel Gee and Associates the same year where he has worked continuously with the exception of a year's sabbatical in MARINTEK. He is Director of Ship Design for Nigel Gee and Associates Ltd. Ed Dudson is a Chartered Engineer and Member of the Royal Institute of Naval Architects.

Hans Jørgen Rambech is a research engineer at MARINTEK. He has been working with model testing and seakeeping calculations with special focus on high-speed vessels. He has also been involved with the development of computer tools to predict manoeuvring characteristics for conventional ships at the early design stage.

1.0 INTRODUCTION

In 1998 the United States Navy Office of Naval Research produced a requirement for a small, fast, highly capable Littoral Surface Craft with the following performance objectives:

i) A calm water speed of 40 knots (later modified to 50 knots).

ii) Self deployable (with a transatlantic range or 4000nm).

iii) Unlimited operations in sea state 4.

iv) Maximum possible operations in sea state 5.

These requirements implied a small high speed platform capable of operating in moderate sea states without slamming and carrying a high deadweight comprising mostly fuel. These requirements of high load carrying and excellent seakeeping could not be met by existing commercial platforms and so a new design was required.

2.0 HULL DESIGN

Hull development work at NGA had previously resulted in a catamaran hull form with excellent resistance characteristics. The powering of this hull design denoted "Vanilla" catamaran easily met the speed / power requirements at ONR. Combined with a motion damping system the seakeeping was also sufficient to meet the requirements of ONR. However, the margins in the seakeeping performance were small.

NGA were given the task of improving the seakeeping of the hull without a significant degradation to the powering. This led to the development of the "ModCAT" hull form, a comparison of the hull lines can be made in Figures 1 and 2.

Figure 1 : Vanilla Catamaran

Figure 2 : ModCAT

The principal dimensions of the Vanilla and ModCAT are shown in Table 1. The main particulars with the exception of draught are identified.

Main dimensions (from input):			
Length between perpendiculars		(m)	54.000
Breadth		(m)	16.772
Draught, midship		(m)	2.379
Data for starboard hull (from geometry)			
Block coefficient	Cb	(-)	0.671
Prismatic coefficient	Cp	(-)	0.716
Mid section area coefficient	Cm	(-)	0.938
Coefficients for data check etc:			
Type		**Specified**	**Calculated**
Displacement (tonnes)		550.00	543.16*
Vertical center of buoyancy	KB		1.431*
Longitudinal centre of buoyancy	LCB		3.622*
Longitudinal centre of gravity	LCG	3.873	3.622*
Longitudinal metacentric height	GMl		102.756*
Transverse metacentric height	GMt		20.288*

* - Applied in the hydrodynamic calculations

Table 1 : Vanilla Catamaran

Main dimensions (from input):			
Length between perpendiculars		(m)	54.000
Breadth		(m)	16.772
Draught, midship		(m)	2.606
Data for starboard hull (from geometry)			
Block coefficient	Cb	(-)	0.680
Prismatic coefficient	Cp	(-)	0.726
Mid section area coefficient	Cm	(-)	0.937
Coefficients for data check etc:			
Type		**Specified**	**Calculated**
Displacement (tonnes)		550.00	549.41*
Vertical center of buoyancy	KB		1.541*
Longitudinal centre of buoyancy	LCB		3.631*
Longitudinal centre of gravity	LCG	3.613	3.631*
Longitudinal metacentric height	GMl		79.190*
Transverse metacentric height	GMt		16.610*

* - Applied in the hydrodynamic calculations

Table 2 : ModCAT

3.0 VERES ANALYSIS

NGA undertook a detailed numerical seakeeping study using the VERES code to assess the benefits of the ModCAT hull form. The study was conducted in a bare hull condition as well as with motion damping.

3.1 Motion Damping System Design

An identical motion damping system has been defined for both catamaran designs. The damping system consists of two T-Foils in the bow and two stern foils in the horizontal plane at the transom. The T-Foils each have a plan area of $4m^2$, which is typical for a vessel of this size. The aft control foils have an area of $0.75m^2$; it is likely that in the full scale a trim tab or interceptor plate would replace the aft control surface. The definition of four control surfaces allows motion damping in pitch, heave and roll.

Yaw control will of course be provided by the waterjets for all the vessels, however since waterjets cannot be simulated in the VERES code it has been necessary to define a small rudder to control the yaw motions particularly in stern seas.

Marintek were subcontracted to design the control algorithm for the motion damping system and this work is covered in section 5.

3.2 RAO Comparisons

The pitch RAO for the Vanilla and ModCAT catamaran designs at 40 knots are shown in Figure 3. The response from the ModCAT is significantly lower with wave periods between 6 and 12 seconds, which coincides with the period of waves the vessel is most likely to encounter. At periods above 12 seconds and below 6 seconds the response of the ModCAT is almost identical to that of the Vanilla catamaran.

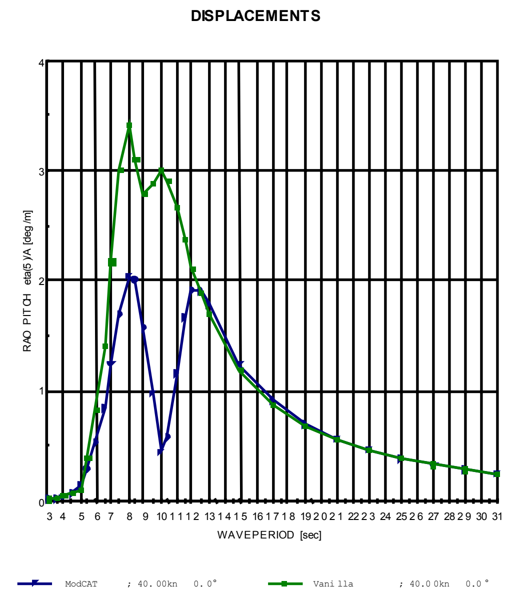

Figure 3

The heave RAO is presented in Figure 4, the Vanilla catamaran has the highest peak response, however the ModCAT has a higher response in waves with a period higher than 10 seconds.

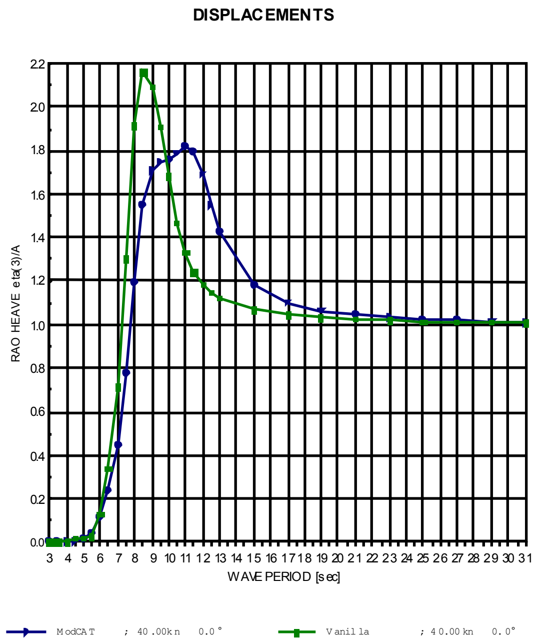

Figure 4

At a speed of 20 knots the ModCAT has a slightly higher peak pitch response, however the response in the period range 5-8 seconds is significantly lower (Figure 5). The heave response of the Vanilla catamaran at 20 knots is highly tuned with very little response outside a period range 6-8 seconds, below 4.5 seconds the Vanilla catamaran shows no response and above 8 seconds the heave response follows the wave amplitude. The heave response from the ModCAT is slightly higher (Figure 6).

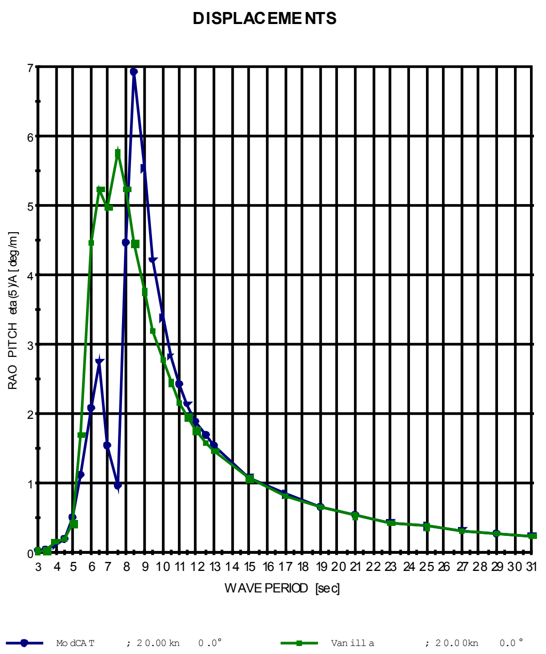

Figure 5

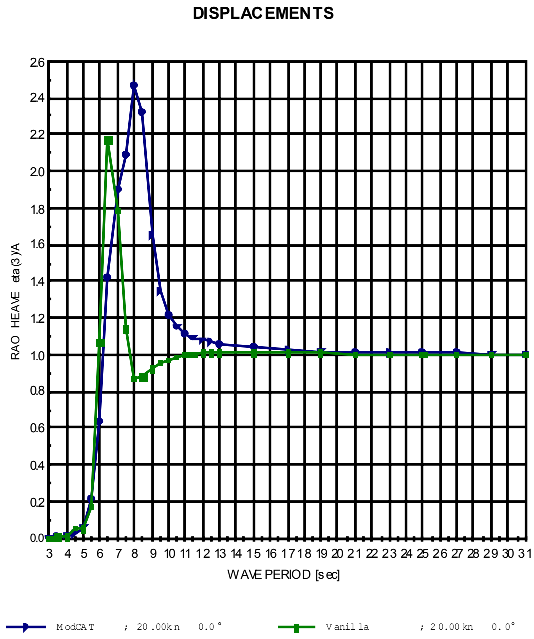

Figure 6

The roll RAO's in Beam seas at both 20 and 40 knots for both designs can be seen in Figure 7, the roll response is highly tuned and the peak of the response is at the natural roll period of the hull. The lower waterplane area of the ModCAT gives the design a lower GM and therefore a slightly higher natural roll period.

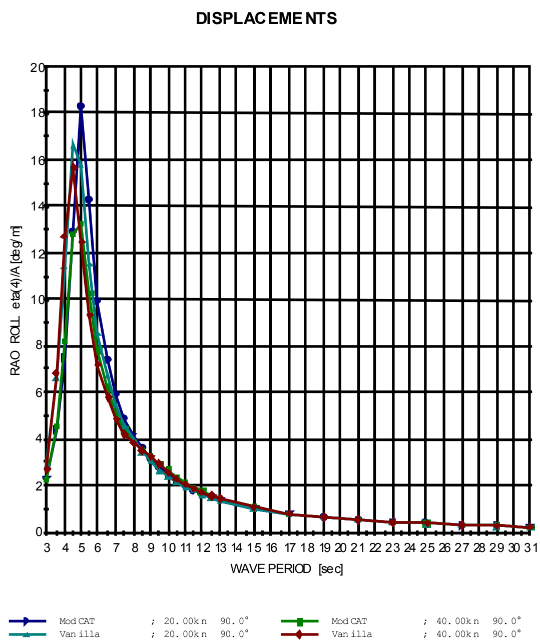

Figure 7

The effect of the motion damping on the pitch RAO for the Vanilla Catamaran is significant as shown in Figure 8. The maximum pitch response with RCS is approximately 50% of the un-damped response. The heave response (Figure 9) also demonstrates a 50% reduction in the maximum response, of particular interest when considering the heave response is the elimination of the resonant response where the heave motion was larger than the wave height.

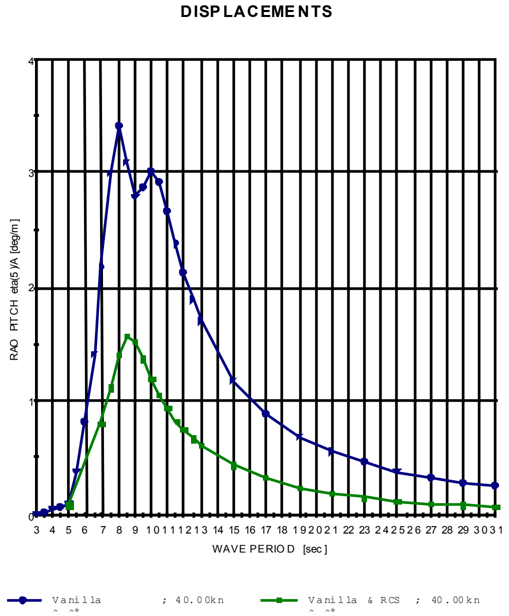

Figure 8

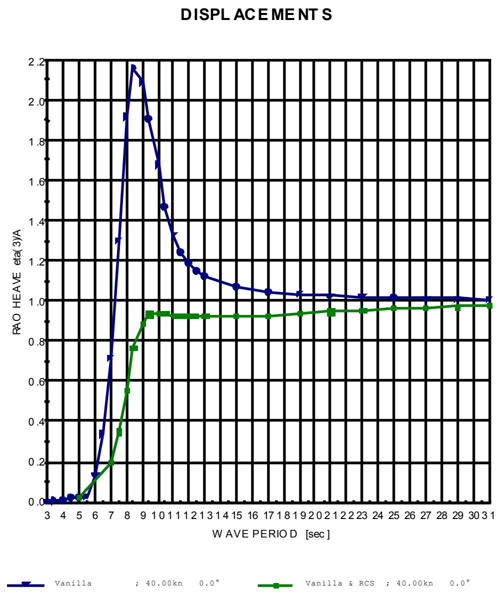

Figure 9

The motion damped pitch response for the ModCAT is compared against that of the un-damped pitch response in Figure 10. In the case of the ModCAT the maximum pitch response is approximately 25% lower than the un-damped ModCAT, however in the frequency band 9-11 seconds the response is actually worse than the un-damped ModCAT, the effect of the RCS system is to eliminate the natural pitch damping characteristics of the ModCAT hull form. As mentioned earlier in the report the motion controller coefficients have not been optimised for the ModCAT and as a result the motion predictions for the damped ModCAT should be interpreted with some caution.

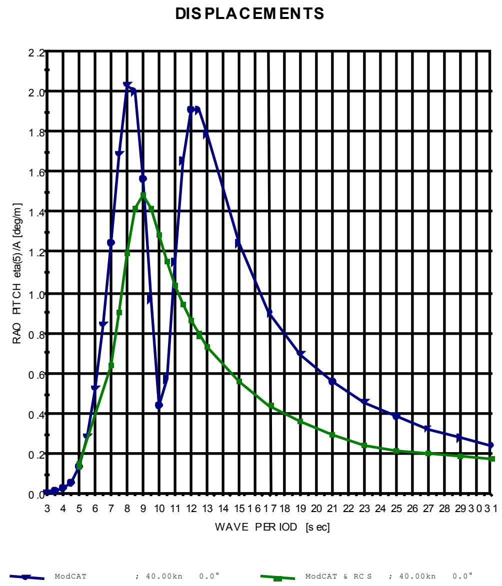

Figure 10

3.3 Motion Damping Analysis - Short Term Statistics

3.3.1 Pitch Response

In Figure 11 the rms pitch responses for the Vanilla catamaran and the ModCAT in head seas at 40 knots with and without RCS are shown. The RMS pitch of the ModCAT is approximately half the value of the Vanilla catamaran. Both the Vanilla and the ModCAT catamarans with motion damping have the lowest RMS pitch. The RMS pitch of the ModCAT is slightly lower than that of the Vanilla catamaran.

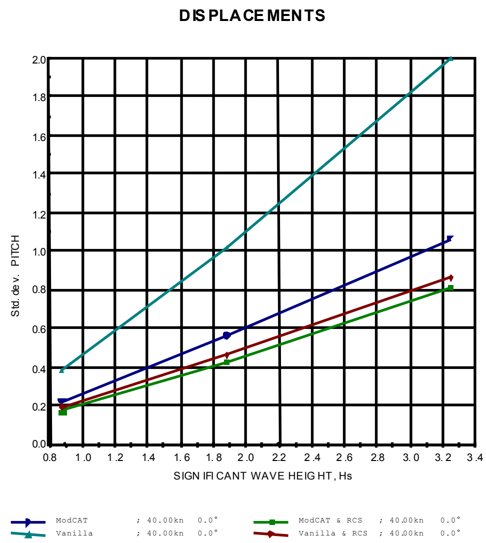

Figure 11

Figure 12 presents the RMS pitch response in head seas at 30 knots, both the Vanilla and the ModCAT designs have higher pitch RMS values at 30 knots than at 40 knots, however the ModCAT has an RMS pitch response of approximately 50% of the un-damped Vanilla catamaran. The Vanilla and ModCAT designs with RCS demonstrate the lowest RMS pitch.

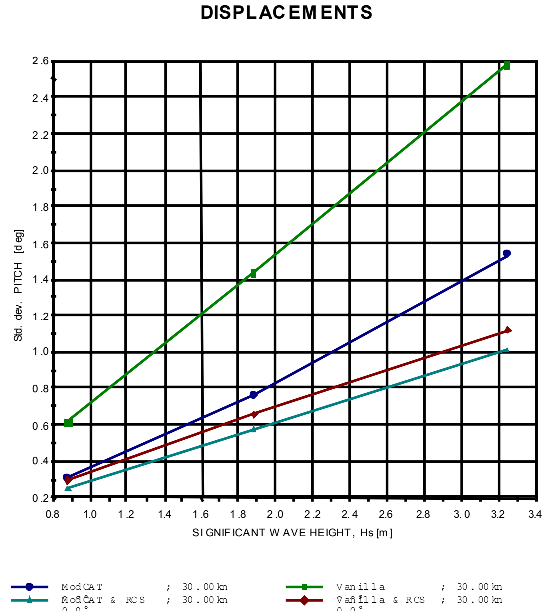

Figure 12

In following seas 30 knots the undamped Vanilla catamaran has a lower response than the undamped ModCAT. The response with motion damping is approximately halved (Figure 13).

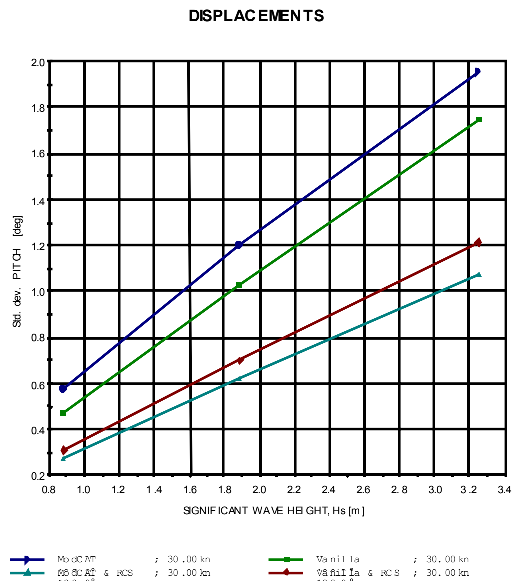

Figure 13

3.3.2 *Heave Response*

The calculated RMS heave at 40 knots in head seas is shown in Figure 14. The ModCAT has a lower RMS heave response than the Vanilla catamaran. With motion damping both catamaran designs are significantly better than the undamped hulls. At 30 knots (Figure 15) the ModCAT design has lower heave motions below SS4, however above SS4 the Vanilla catamaran has a slightly lower RMS heave response. The RMS Heave of the catamarans with RCS is significantly lower than undamped catamarans.

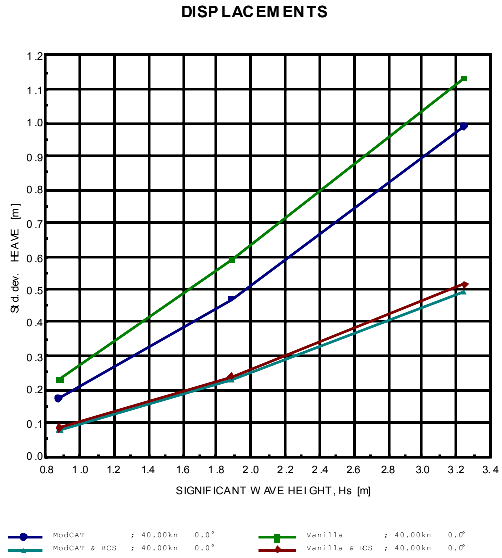

Figure 14

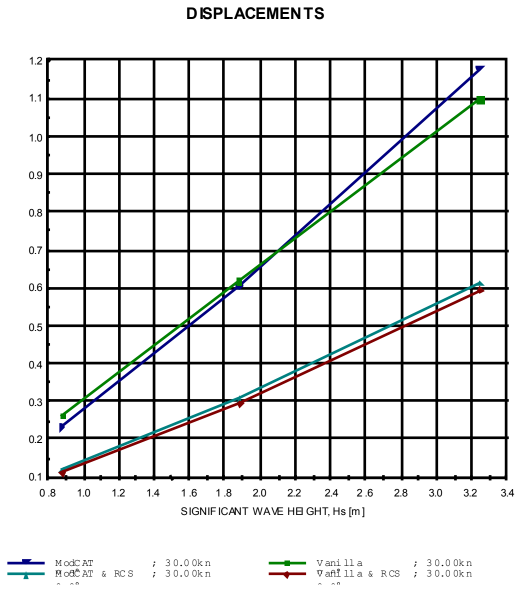

Figure 15

3.3.3 *Vertical Accelerations*

Vertical Accelerations are presented for forward perpendicular

The vertical accelerations of the ModCAT at the FP (Figure 16) are significantly lower than those of the Vanilla catamaran. With RCS the vertical accelerations are identical for the Vanilla and the ModCAT.

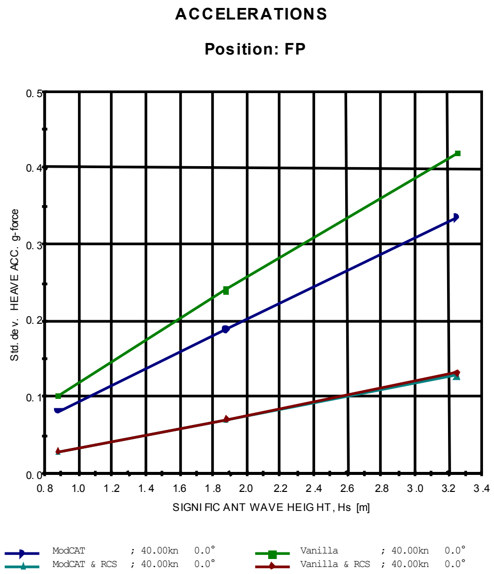

Figure 16

The VERES analysis clearly shows a significant difference between the response of the ModCAT and Vanilla catamaran without motion damping. However, the predicted differences with motion damping are very small.

4.0 RESISTANCE TESTING

Resistance tests were carried out in May 2001, at Marintek in Trondheim with models of both the optimised Vanilla catamaran and the ModCAT. Calm water resistance results are shown in Figure 17. It can be seen that at speeds above 30 knots the resistance of the ModCAT is higher than that of the Vanilla catamaran at the same displacement, and that this difference increases with increasing speed, such that at 40 knots the difference is about 6% and at 50 knots the difference is about 12.5%. Trimming the ModCAT by the head significantly reduced the dynamic wetted area of the ModCAT and the resistance at high speed was reduced significantly. The results are shown in Figure 18. It can be seen that whilst the resistance of the ModCAT up to 40 knots is similar to the untrimmed model, the trimmed vessel exhibits lower resistance above 40 knots, so that between 45 and 50 knots there is negligible difference between the ModCAT and the Vanilla catamaran. The lines of the ModCAT have since been redrawn, effectively incorporating the trim change but with levelled deck line. If a larger tank testing budget had been available it was felt that further improvements could be made, not only to the ModCAT, but also to the optimised Vanilla, and it is to be expected that if both hull forms were further optimised then the resistance of the Vanilla catamaran at high speed and calm water would always be better than that of the ModCAT because of the lower wetted surface area. However, the main objective of achieving a speed of 45 knots, the given input power of 2 x 8283kW was achieved and the programme proceeded to the next phase.

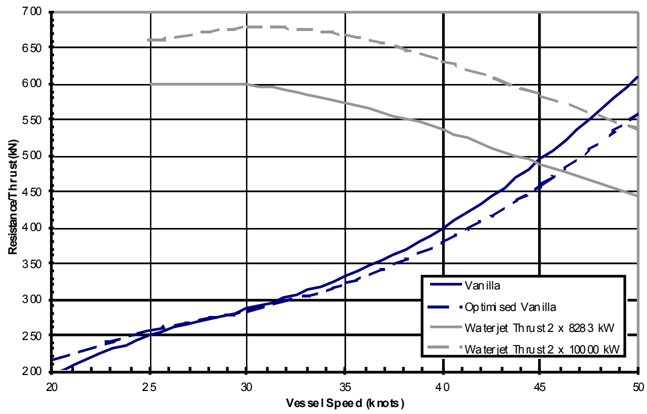

Figure 17 – Calm Water Resistance

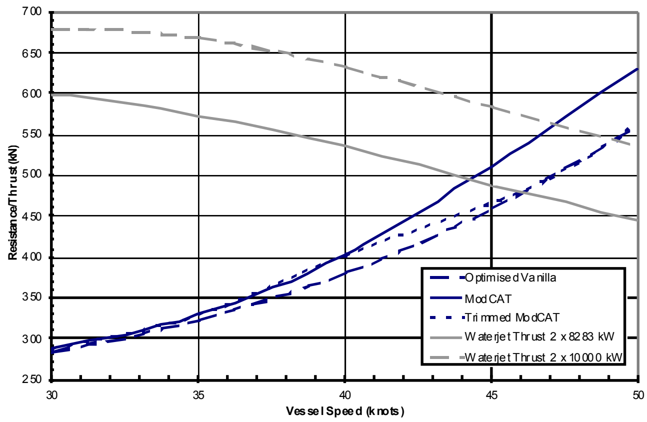

Figure 18 – Calm Water Resistance

5.0 SEAKEEPING TESTS (MARINTEK)

The initial seakeeping tests were carried out in the full length-towing tank at Marintek, testing both the Vanilla and the ModCAT in sea state 3, 4 and 5 in head and following sea. Model scale for both models where 1:15. "The Winner" of the two would proceed into the ocean basin at Marintek, where further seakeeping tests would take place in oblique seas.

The set up in the towing tank was quite simple, with identical setup for both models. The photo below shows one of the models in action.

Figure 19 – Model in the towing tank

As the photo indicates, both models were self-propelled with identical stock Marintek waterjet units, completely free in pitch and heave, but fixed in yaw. The models were free in surge as well, within the ability of the person running the towing wagon keeping up with the small model speed changes. The weights of the flexible light-weighted aluminium struts, as indicated on the photo, with the purpose maintaining yaw control was included in the model displacement.

5.1 RCS Tuning

Prior to the model testing, quite extensive RCS control parameter tuning took place in the software program VERES. The purpose was to have a set of pre-tuned control-parameters ready, so valuable and expensive time in the towing tank having to tune the parameters there was avoided. Nevertheless, some time was spent verifying the results from the VERES work before initiation of the contracted seakeeping tests.

The tuning of the parameter set required doing lots of simulations according to a quite extensive matrix where the different control parameters were varied in a systematic way. All the tuning simulations where done in the time-domain. The control algorithms are described below.

T-foils in the bow:

$$\delta_f = k_{\theta f} \cdot (\theta_{set} - \theta) - k_{qf} \cdot q + k_{wf} \cdot w_f + \delta_{offset} \pm k_{pf} \cdot p$$

δ_f Foil angle (deg), command signal
$k_{\theta f}$ Gain Pitch, foils (-)
k_{qf} Gain pitch rate, foils (s)
k_{wf} Gain heave velocity, foils (deg.s/m)
k_{pf} Gain roll rate, foils (deg.s/deg). Introduced during oblique sea tests, not initially in the towing tank
δ_{offset} Foil offset point, 0.5deg chosen (deg)
θ_{set} Pitch set point, 1.0deg bow up chosen (deg)
θ Pitch angle of ship (deg)
q Ship rate of Pitch (deg/s)
w_f Ship heave velocity at long. pos. of foils (m/s)
p Ship rate of roll (deg/s)

Interceptors at the transom:

$$z_i = -k_{\theta i} \cdot (\theta_{set} - \theta) + k_{qi} \cdot q + z_{offset} \pm k_{pi} \cdot p$$

z_i Interceptor deflection (mm), command signal
$k_{\theta i}$ Gain pitch, interceptors (mm/deg)
k_{qi} Gain pitch rate, interceptors (mm.s/deg)
k_{pi} Gain roll rate, interceptors (deg.s/deg). Introduced during oblique sea tests, not initially in the towing tank
z_{offset} Interceptor offset point during testing, 5mm model scale, (mm)
θ_{set} Pitch set point, .0deg bow up chosen (deg)
θ Pitch angle of ship (deg)
q Ship rate of Pitch (deg/s)
p Ship rate of roll (deg/s)

The tuning in the time-domain in VERES were all done as calm water simulations, with perfect sine deflections on the force producers at varying frequencies (the interceptors were also modelled as foils during simulations). The control algorithms were then superimposed on the sine signals, with a subsequent damped response. The control parameter set with best results (most damping at the important frequencies) where found to be:

	Bow controller				Stern controller			
	K_w	K_p	K_θ	K_q	K_w	K_p	K_θ	K_q
Full scale	0,09	2	2,5	2,5	0	2	1,25	1,25
Model scale	19,972	0,516	2,5	0,645	0	0,516	1,25	0,323

Figure 20 – Control Parameters Set

5.2 Model Tests

The control algorithms and parameters given in Figure 21 where used during the model tests. An MRU-unit (Seatex) installed in the model gave the appropriate model pitch rate, and later roll rate in the ocean basin. The heave velocity was derived from two accelerometer sensors, one over each T-foil in the bow, with signals that were integrated online and band-pass filtered before processed by the control algorithms. Pitch angle was furnished by the positioning system in the tank and later the basin.

Figure 21 and 22 gives the measured heave and pitch response in head sea in irregular waves as short-term statistics with RMS values given. Compared to the initial VERES calculation as presented in Figure 11, 12, 14 and 15, the agreement is quite good.

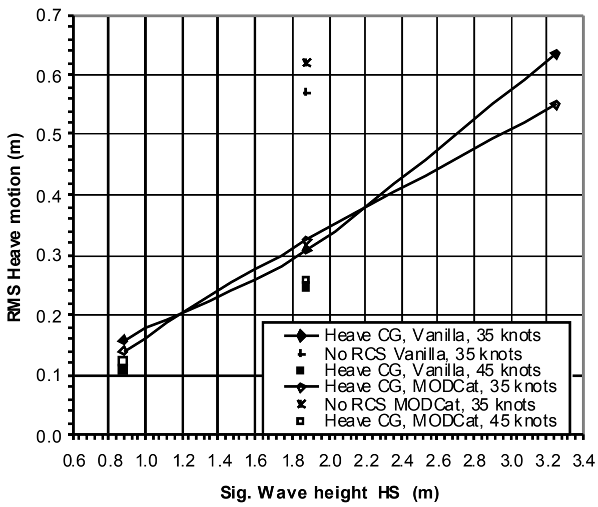

Figure 21

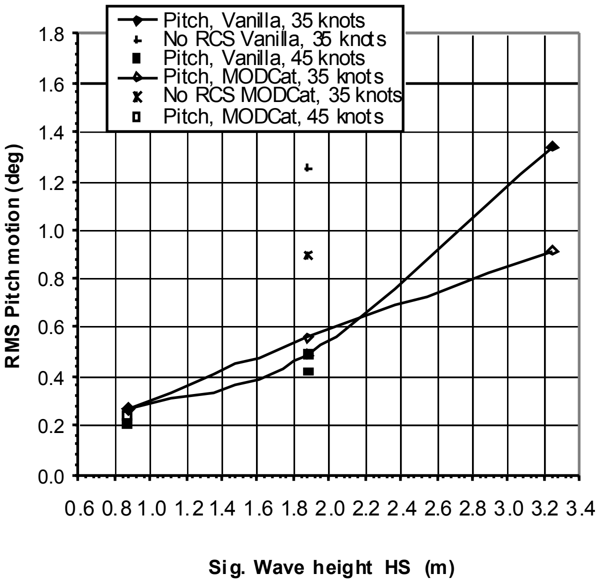

Figure 22

The evaluations of all the model test results so far in the testing programme, led to the conclusion that the ModCAT should proceed to the final tests in the ocean Basin. Waterjet nozzles with a rudder servo and an appropriate autopilot were introduced onto the model prior to the seakeeping tests in oblique seas. The model was repainted navy-grey and a simple superstructure was manufactured. Figure 23 gives a photo of the model during the ocean basin oblique sea tests.

Figure 23 - Model during oblique seakeeping tests

The model was completely free running during the tests. The tests confirmed the good seakeeping characteristics found from the calculations as well as previous model tests. The T-foils were damping the motions very effectively. To give an example, Figure 24 gives the measured RMS vertical acceleration at three different positions: FP, CG and AP. As the figure indicates, the vertical accelerations at the forward perpendicular FP and at the centre of gravity CG are almost identical, with the highest measurement at the aft perpendicular AP. Quite unusual for any type of ship. The stern force producers, or interceptors, were found not to be as effective as T-foils, especially since the ship waterline area stiffness astern would dominate in conditions with wave peaks astern. The interceptors are not capable of generating a downward force astern, except by retraction reducing the lift force, which might not be sufficient in larger wave conditions to fully dampen the wave induced motion astern compared to the capability of a T-foil for instance.

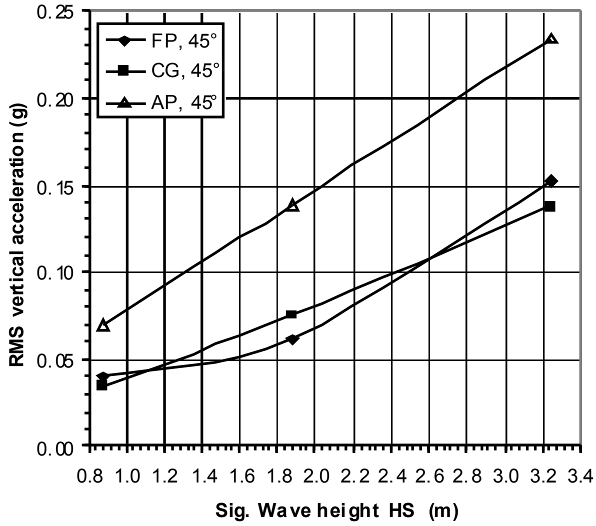

Figure 24

6.0 RESULTS

The results from the ocean basin test enabled a complete documentation of the motions and accelerations of the ModCAT in sea states 3, 4 and 5. Of critical importance to the programme was the issue of speed loss in various sea states. Figure 25 shows typical speed loss values for the vessel operating in head seas. In sea states 3 and 4 the self-propelled model was powered at a level, which gave a speed of 45 knots in calm water and then the average speed loss measured. It can be seen that the ModCAT loses less than 0.5 knot in sea state 3 and only just over 1 knot in sea state 4. In sea state 5 the vessel was powered for a calm water speed of 35 knots and a speed loss of about 5 knots resulted. The design point for this vessel was to achieve 40 knots in sea state 4 and so the result of 43.7 knots was more than acceptable.

	Speed	Speed Loss		Speed	Speed Loss
Vessel	Calm Water (kts)	SS3 (kts)	SS4 (kts)	Calm Water (kts)	SS5 (kts)
Vanilla	45	0.55	1.7	35	5.83
ModCAT	45	0.42	1.3	35	4.99

Figure 25 – Summary – Head Seas

Figure 26 shows a comparison of the measured and predicted values vertical acceleration at the FP for both the Vanilla and ModCAT hullforms with an active motion damping system. It can be clearly seen that the agreement between the predicted and measured values for the ModCAT is excellent, however, the agreement for the Vanilla catamaran is good up to a wave height of 1.9m and then the predicted values are significantly lower than those measured. The explanation for this is that in a significant wave height of 3.25m, the Vanilla catamaran started to experience slamming on the underside of the wet deck.

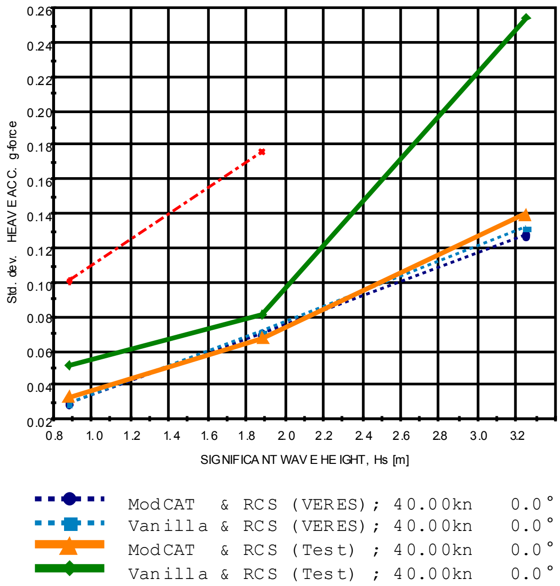

Figure 26

7.0 X-CRAFT BUILD

Figure 27 shows a computer rendering of the craft in its current configuration. The flight deck is certified for twin spot landing of H-60 series helicopters. The mission deck is configured to carry 12 of containerised mission modules.

This vessel is larger than the original ModCAT design with a waterline length of 73m. It is propelled with a CODOG propulsion system consisting of MTU 16V 595 diesels and LM2500 gas turbines. The vessel is capable of speeds up to 60 knots.

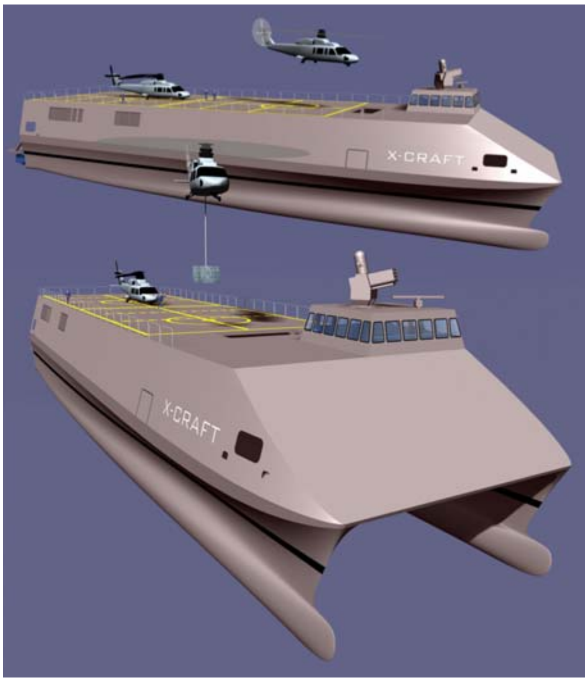

Figure 27 – LSC(X) Craft

8.0 CONCLUSIONS

a) Historically catamaran craft have been criticised for poor ride comfort in higher sea states and relatively high speed loss in these conditions.

b) The LSC(X) has been designed specifically to carry high deadweights in moderate to high sea states. The design features a high wet deck clearance, an optimised fore body, and a large motion damping system.

c) The design process has shown that if designed for operation in higher sea states, catamarans can provide excellent ride quality and low speed loss.

Acknowledgement: Arne Kjørsvik at Marintek doing all the RCS tuning in Veres.