Ocean Transits in a 50m, 45 knot Catamaran – The Minimisation of Motions and Speed Loss

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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 designated LSC(X). A two year development programme at NGA produced a new hull form, the Modcat, which when coupled with a powerful ride control 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.

James Roy graduated from the University of Southampton with an honours degree in Yacht & Powercraft Design and then joined Nigel Gee and Associates Ltd (under contract) to undertake a joint research project with academia. Upon completion James joined Nigel Gee and Associates Ltd (full time) in 1997 as Assistant Naval Architect, promoted to Naval Architect in early 1998, and Senior Naval Architect in 2001.

1. 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 45 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.

v) A capital cost for the hull machinery, and electrics, of US Dollars 20 million.

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 radically new design was required.

The Office of Naval Research initially let a contract to Pacific Marine in Hawaii to investigate a number of hull forms, including catamarans, SWATH derivative hull forms, SES, and other novel platforms if appropriate. Nigel Gee and Associates Ltd initially acted as subcontractor to Pacific Marine to produce data for catamarans, SES and sponson assisted monohulls, with Pacific Marine concentrating on SWATH derivatives based on their earlier work on Navatek SWATH, Slice and Midfoil. The candidate configurations are shown in Figure 1.

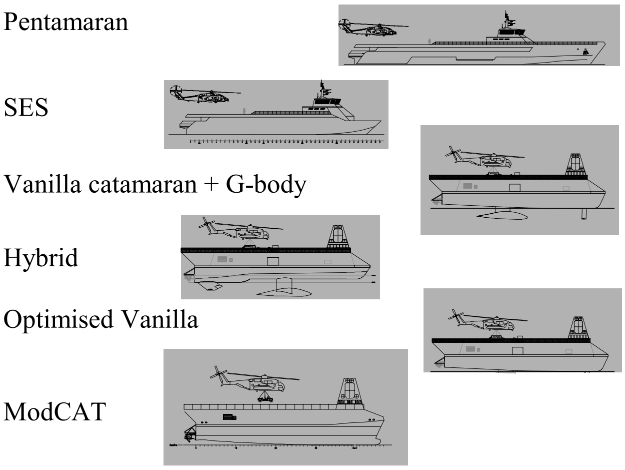

Figure 1 – Candidate Configurations

Candidate configurations were evaluated initially by computational methods, and in the case of the more promising configurations, later tank tests. The initial configurations were reduced to a short list as follows:

i) Pentamaran – a Pentamaran platform to meet the requirements was designed and resulted in a vessel having very low motions and speed loss, achieved without the use of a ride control system, and the capability to self deploy over long distances and carry the required payload. However, the very nature of Pentamarans and other sponson assisted monohulls, yields a very long hull for any particular requirement. The Office of Naval Research were specifically looking for a small (short) vessel for this application and the Pentamaran was considered inappropriate. The Pentamaran is now under consideration for a larger ship requirement of the United States Navy, the Littoral Combat Ship (LCS).

ii) Surface Effect Ship (SES) – an SES design was produced and as expected this had the lowest powering requirement of all options considered. However, the seakeeping and speed loss of this small vessel when operating in the open ocean were not good enough to meet the design criteria and this platform was rejected.

iii) Catamaran fitted with a submerged buoyant hydrofoil. A number of catamaran variations were studied and the basis vessel was referred to in this study as the "Vanilla" version. This catamaran was fitted with a two dimensional buoyant hydrofoil (G-Body) designed by Pacific Marine and based on the body fitted to their Midfoil design. CFD analysis indicated that the Vanilla catamaran plus G-Body combination would yield high lift to drag ratios, consequent low powering, and good seakeeping. Later tank tests however, indicated that there were very significant adverse interaction effects between the body and the catamaran hull which increased drag, reduced the effectiveness of the combination. Following tank tests the CFD analysis was re-evaluated resulting in much lower lift to drag ratio predictions.

iv) Hybrid - the Hybrid design used a heavily modified catamaran with high deadrise sections and a stepped keel line to enable the forward part of the vessel to fly when supported on the foil at speed. Once again, when testing this combination on the test tank there was some interaction and control problems. The Office of Naval Research felt that the whole area of fitting of the SWATH-like bodies or buoyant hydrofoils to catamarans merited further research and this is current underway at Pacific Marine. It were decided to proceed with the LSC(X) programme on the basis of building, launching and trialing a catamaran hull, then retrofitting a modified G-Body following the above mentioned research efforts.

v) Optimised Vanilla Catamaran – following the decision to proceed with a catamaran hull, the Vanilla catamaran was further optimised particularly in way of the transom and resistance was reduced further. The vessel performed well in sea state 4, but it was clear that motions in sea state 5 could be improved if very significant changes were made to the fore body.

vi) Modcat – the Modcat design was based on the Vanilla catamaran but with heavily modified forward sections to improve the seakeeping. The drag of the Modcat was higher because of higher wetted surface on the fore body but seakeeping was significantly improved and this vessel was selected as the best hull form to proceed with for the LSC(X) full scale design.

2. TANK TESTS

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 2. 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%. During the tests a higher than expected stern squat on the Modcat indicated that improvements could be made if the lines were modified. Modification to the lines was simulated by trimming the Modcat by the head and the results are shown in Figure 3. 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 should 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.

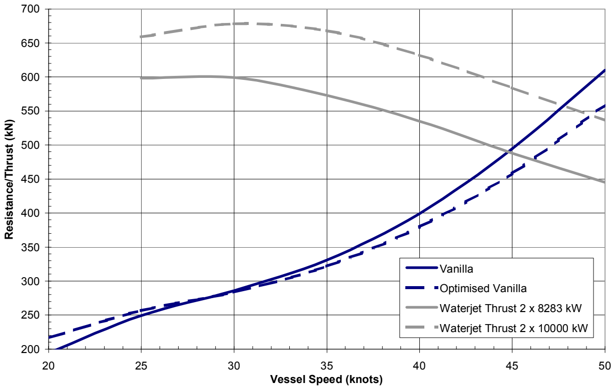

Figure 2 – Calm Water Resistance

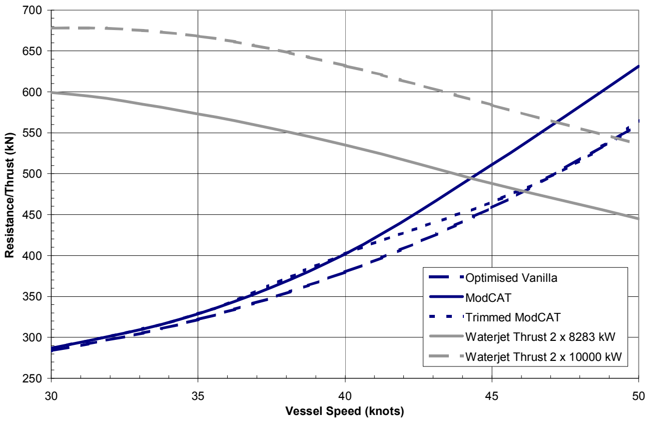

Figure 3 – Calm Water Resistance

3. VERES ANALYSIS

Motions and accelerations of the Modcat and Vanilla catamaran was initially estimated using the VERES software licensed from Marintek in Trondheim.

The theory applied in the VERES program is based on linear, potential, strip theory. The theory is developed for moderate wave heights inducing moderate motions on a ship with a length which is much larger than the ship breadth and draught. In addition the change in cross-sectional area as a function of longitudinal position should be slow.

In short the basic assumptions in the VERES program are as follows;

- The ship is assumed to oscillate harmonically with frequency equal to the frequency of encounter. No transient effects due to initial conditions are accounted for. No hydro-elastic effects accounted for.

- A linear relation is assumed between the response and the incident wave amplitude. This will not be correct in high sea states where slamming and water on deck may occur. This also assumes that the hull should be close to wall sided at the free surface.

- The superposition principle can be used to derive the loads and motions in a sea state.

- Potential theory can be applied. The fluid is assumed to be homogenous, non-viscous, irrotational and incompressible. However, viscous roll damping can be accounted for by means of empirical formulas.

- The length of the hull is assumed to be much larger than the breadth and the draught.

- In the traditional strip theory, the three-dimensional hydrodynamic problem can be reduced to a set of two-dimensional strips, without interaction between the strips. Total forces can be obtained by integrating cross sectional two dimensional forces over the ships length. This means that three dimensional effects are neglected.

- In the High Speed Theory, interaction from the strips upstream are accounted. Total forces can be obtained by integrating the cross-sectional two-dimensional forces over the ships length. The theory has been denoted as a 2½ dimensional theory.

- In the High Speed Theory with hull interaction the standard high speed theory has been modified to account for hull interaction effects.

- The vessel is symmetric about the centreline.

Ship motions obtained by the program show good correlation with experiments even at wave conditions which are outside the limits of the theory.

The principal particulars of the "Vanilla" catamaran and the "Semi-Swath" design are similar; both have the same main dimensions and the same displacement. The VERES calculations have been performed at the anticipated full load displacement of 550 tonnes.

The hull lines for the "Vanilla" catamaran are a further development of the catamaran previously tested at MARINTEK during October 2000. The hull lines for the "ModCat" have been designed to provide a improved ride quality without significant degradation in vessel speed.

A sample output from the VERES analysis showing rms vertical accelerations is given in Figure 4. The figure shows the vertical accelerations at the forward perpendicular, centre of gravity and after perpendicular. The figure shows results for the vessel with and without a ride control system.

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 possible that in the full scale vessel the aft control surface could be replaced by a trim tab. The definition of four control surfaces allows motion damping in both 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.

The effectiveness of the ride control system is very dependant upon the controller coefficients which determine the deflection angles on the control surfaces based on the attitude of the vessel. The VERES code uses a generic controller algorithm to generate the foils response angle, which is described below :

$$\delta = -K_G \frac{K_1 + K_2.s + K_3.s^2}{b_1 + b_2.s + b_3.s^2} \eta_x$$

Where

δ	is flap angle
K_G	is overall gain setting
K_1	is motion sensitivity
K_2	is velocity sensitivity
K_3	is acceleration sensitivity
b_1, b_2 & b_3	are fixed controller coefficients
s	is the Laplace Transform Operator (d/dt)

The controller coefficients for each response are unique to each of the control surfaces, as a result optimising the magnitude of the controller coefficients to maximise the motion damping and therefore minimise vessel motions is very time consuming.

NGA subcontracted MARINTEK to investigate suitable controller coefficients for the Vanilla catamaran. MARINTEK used a time domain code to simulate the motions of the vessel at 40 knots in heads seas, with the previously described foil arrangement. MARINTEK investigated two different controller types. The first a simple controller based only on roll and pitch feedback, and a more complex controller based on roll, pitch and heave velocity feedback. NGA have used the more complex controller in the calculations of the performance of both vessels with ride control. The results of the MARINTEK motion study are presented in Appendix A.

It should be noted that the same controller coefficients designed for the Vanilla catamaran have been applied to the ModCat, it is likely, therefore, that some improvement in the motions of the ModCat with RCS could be achieved with optimisation.

It can be seen that without ride control the acceleration levels on the ModCat are significantly less than that on the Vanilla catamaran. With ride control, results for the two hull forms are virtually identical and, therefore, the preliminary conclusion was that the addition of a ride control system would allow the full scale craft to exploit the resistance benefits of the Vanilla catamaran hull form without incurring any seakeeping penalty.

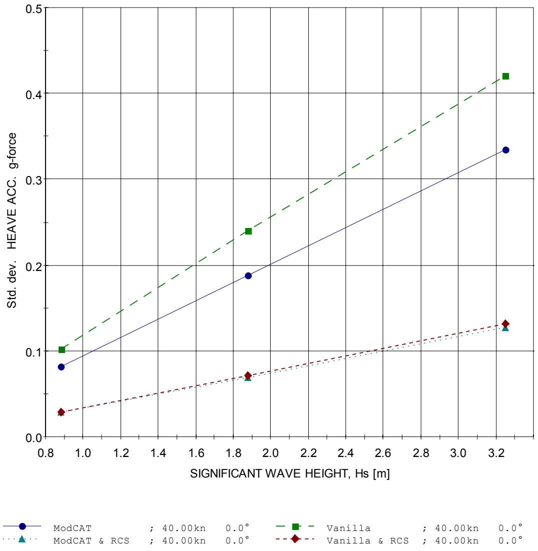

Figure 4 - RMS Vertical Acceleration @ FP

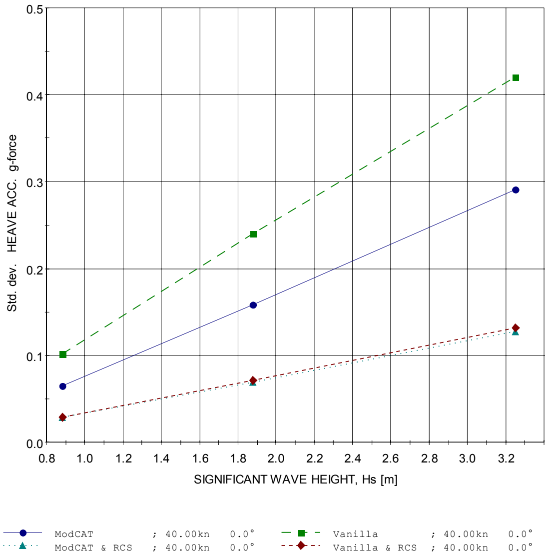

Figure 4 - RMS Vertical Acceleration @ CG

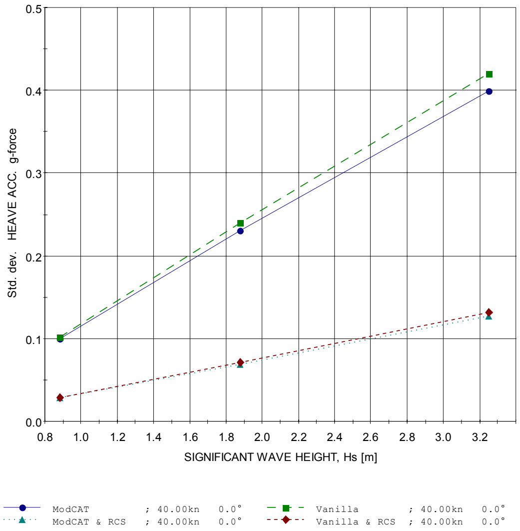

Figure 4 - RMS Vertical Acceleration @ AP

Further tank testing in September 2001 in head seas on the towing tank was intended to validate the VERES analysis. The results in vertical accelerations at the centre of gravity in head seas are shown in Figure 5. All results are for the vessel fitted with a ride control system. It can be seen that the acceleration levels measured on the Modcat with ride control system correlate very closely with those from the VERES analysis and in fact are almost identical. The results from the Vanilla catamaran are close to those from the VERES analysis in sea state 3 and 4, but significantly different in sea state 5. This difference is almost entirely due to slamming of the Vanilla catamaran in head seas in sea state 5, and this non-linear behaviour is not identified in the VERES analysis. The results clearly show the advantage of using the Modcat hull form.

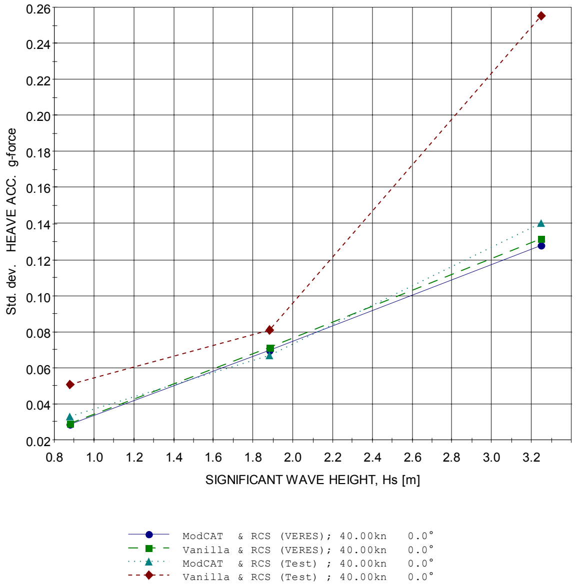

Figure 5 - RMS Vertical Acceleration
@ FP (Head Seas)

4. OCEAN BASIN TESTS

Following the towing tank tests and the VERES analysis it was decided to undertake a full programme of ocean basin tests with the Modcat hull form.

Ocean basin tests were carried out in the large ocean basin at Marintek in Trondheim. A 1:15 scale model of the Modcat with T-foil and interceptor ride control system (Figure 6) was tested in sea states 3, 4 and 5 and at headings of 0°, 45°, 90°, 135° and 180° (Norwegian sign convention 0° head seas, 180° following seas). Speeds ranged from 30-45 knots and there was also a limited amount of testing with the vessel just underway at speeds of between 0-4 knots to investigate behaviour when carrying our mine counter measures work or launching and recovering boats over the stern. Finally some failure cases were investigated to determine the behaviour of the vessel in the event of ride control system failure, or total malfunction.

Figure 6 – ModCat Model

5. 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 7 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 7 – Summary – Head Seas

It was also a requirement that the vessel should be fully operational in sea state 4. Fully operational means able to carry out helicopter landing, refuelling and take-off, and be able to meet habitability criteria for long ocean transits. In total some 20 criteria had to be met of which the most important were:

- Vertical accelerations not to exceed 0.1g rms
- Pitch not to exceed 2° rms
- Roll not to exceed 3° rms

At the time of the tests ONR and the US Navy were unable to provide a lateral acceleration criterion and NGA self imposed a level of 0.05g rms. Figure 8 shows the output from VERES (validated by the tank tests) for the Vanilla catamaran and ModCat operating in sea state 4. For the vanilla catamaran it can be seen that between approximately 105° (wave just abaft the beam) and 150° (waves just aft of stern quartering condition) and at speeds below 34 knots, the vessel does not meet operational limitations. The only operational limitation which was not met in this region was that of lateral acceleration. At all other headings and at speeds above 22 knots, the vessel was fully operable in sea state 4. The results clearly indicate that in order to meet operational criteria the vessel should not be operated at low speed or with the seas predominantly from the beam to stern quartering direction.

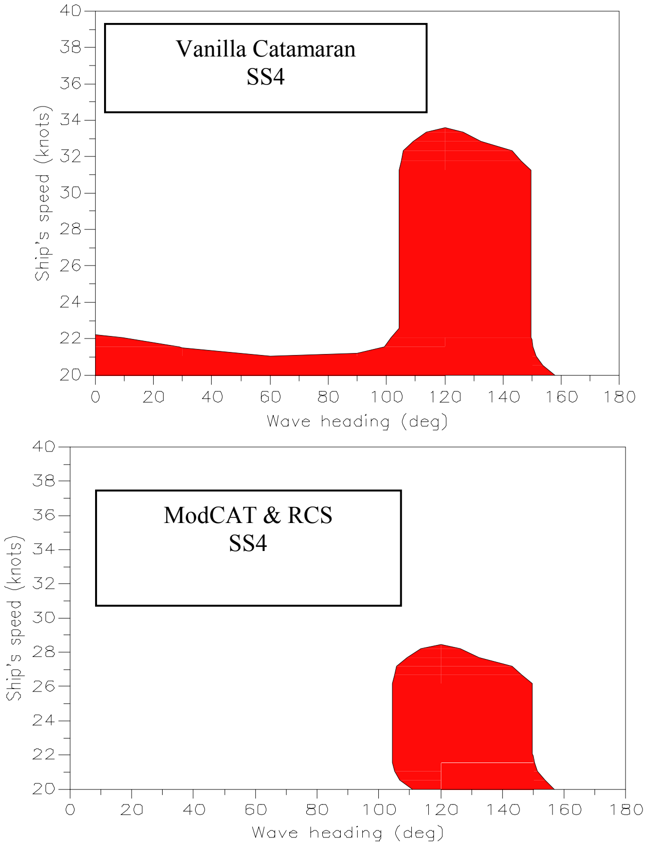

Figure 8 – Operational Limitations

Similar results were shown for the Modcat, but in this case the vessel met all operability criteria at speeds above 30 knots (compare 34 knots for the Vanilla) and when excluding the stern quartering condition met all operability criteria at speeds above 12 knots (compare 22 knots for the Vanilla). For both vessels a slight increase in the permissible lateral accelerations enable the vessel to be fully operational at all wave headings.

Figure 9 shows a similar plot for the vessels operating at the lower end of sea state 5 (significant wave height 2.5m). In this case, the Vanilla catamaran fails the operational limitations in all but following sea conditions. The dark area in the diagram indicates failure to meet operational limitations as defined by VERES and the lighter portion of the diagram indicates failure to meet operational limitations as observed during tank tests. In this region, VERES fails to predict the slamming behaviour of the Vanilla catamaran.

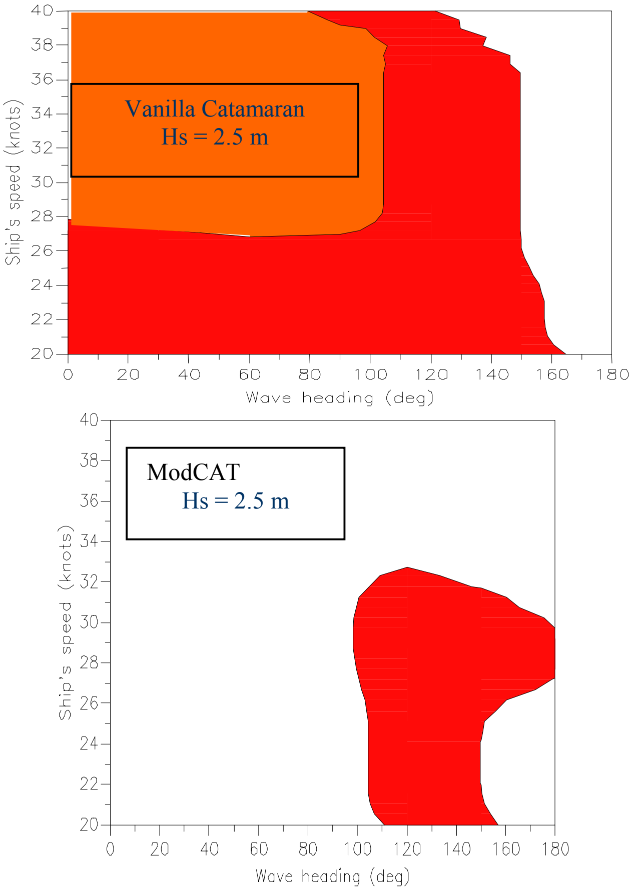

Figure 9 - Operational Limitations

The Modcat is almost as operational in this sea state as in the sea state 4 condition, and is fully operational at speeds above 20 knots in all headings, except beam to stern quartering seas, and meets operational criteria at all headings at speeds above 32 knots. The Modcat as defined has now been accepted by the US Navy Office of Naval Research and a contract placed with Nigel Gee and Associates Ltd to produce a contract design for shipyard quote early next year. It is anticipated that the first vessel will be operational during 2004.

6. ARRANGEMENT AND FULL SCALE PERFORMANCE

Figure 10 shows a general arrangement of the craft as envisaged at the beginning of 2002 following the completion of all tests and concept design exercises. The craft can land and refuel one large or two small helicopters on the large flush upper deck, and carry a number of containerised mission modules on the hangar deck below. Propulsion of this variant is by two TF100 gas turbine packages driving large KaMeWa waterjets.

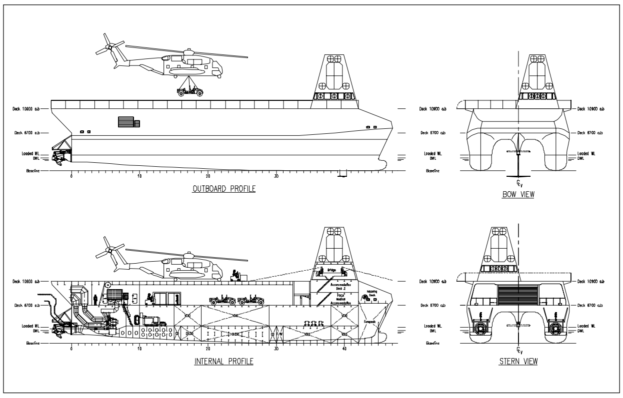

Figure 10 – General Arrangement

Performance of the vessel is shown in Figures 11, 12 , 13 and 14. Figure 11 shows the speed possible at various displacements and powers. The proposed installation of just over 22,000hp gives a speed of 50 knots in the lightship condition and a speed of 45 knots with approximately 150 tonnes of disposable load.

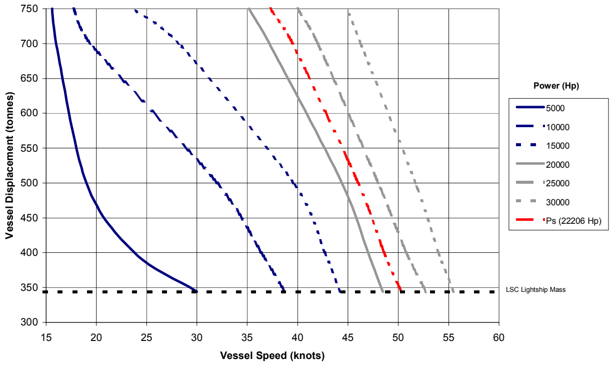

Figure 11 - LSC Performance

Endurance is shown in Figure 12 and range in Figure 13. If the high disposable load of just over 400 tonnes is used entirely for fuel then high speed ocean transits at speeds between 20 and 40 knots over a range in excess of 4,000nm are possible. Much higher ranges are clearly possible at lower speeds, with a range of approximately 10,000nm at 10 knots. The range figures are presented in a different way in the self deployment chart Figure 14, which indicates the range of the craft versus transit speed for various residual loads at the end of the trip. The chart shows that a 4,000nm transit at 30 knots can be achieved with 50 tonnes remaining onboard at the end of the transit.

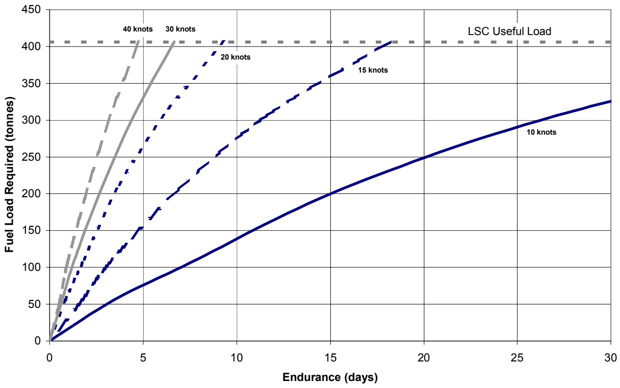

Figure 12 - LSC Endurance

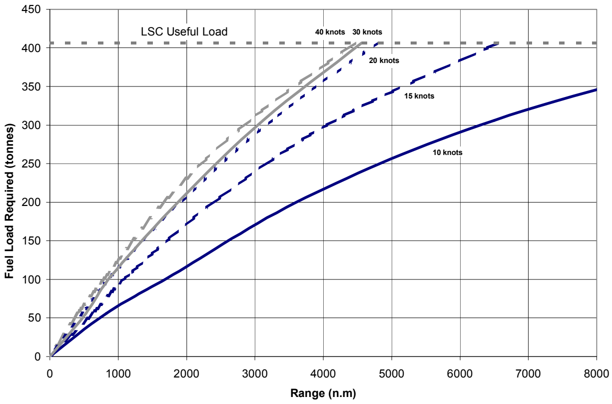

Figure 13 - LSC Range

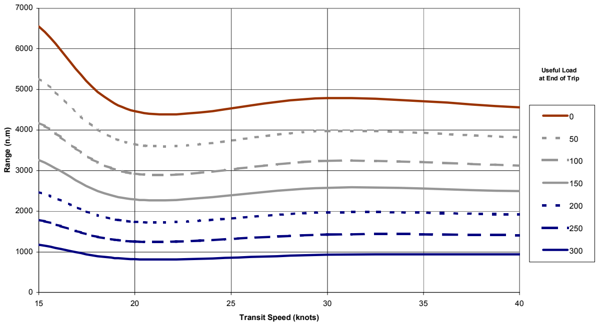

Figure 14 - LSC Self Deployment

As stated above, the US Navy is now proceeding to commission the build of the first LSC(X) and in the last six months a performance specification has been set which increases the required speed of the craft as well as increasing payload and range requirements. The craft presently being designed is considerably larger than the original LSC(X) but uses the same hull form. The arrangement of the present vessel is shown in Figure 15.

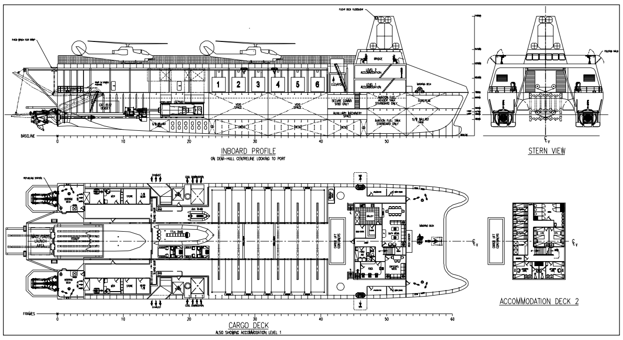

Figure 15 – Arrangement September 2002

This craft is propelled by two LM2500 gas turbines, driving waterjets with auxiliary loiter propulsion by diesel engines through a CODOG box. Computer renderings of the vessel are shown in Figure 16.

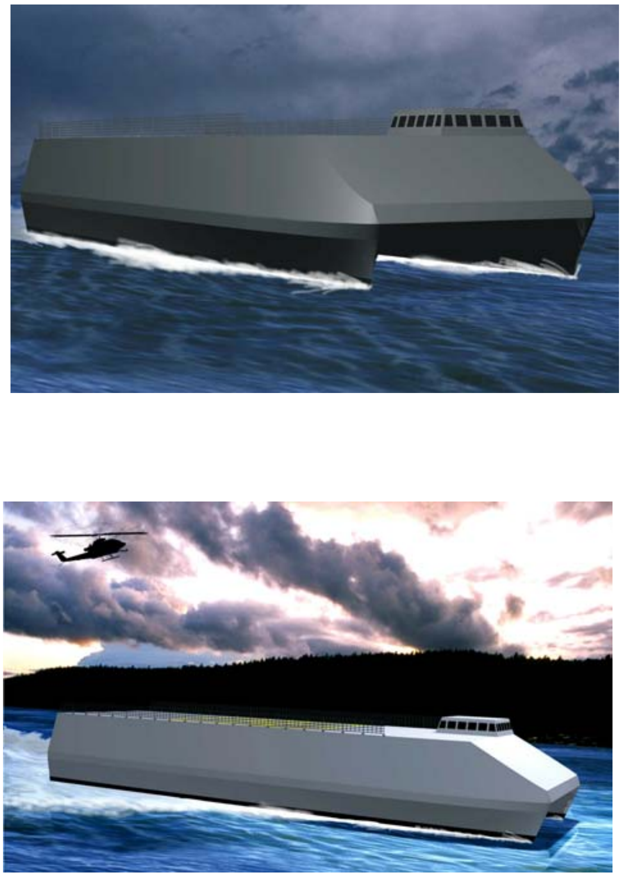

Figure 16 – LSC(X) Craft

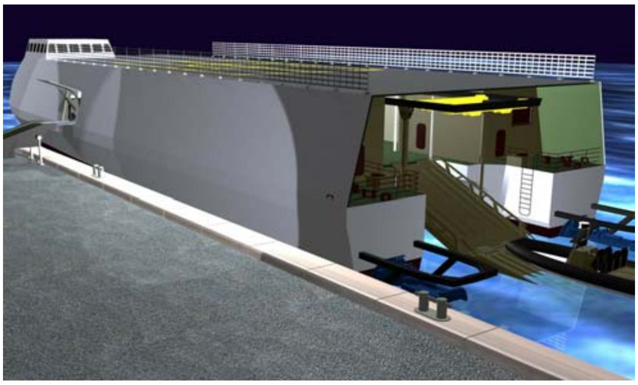

Figure 16 – LSC(X) Craft cont.

7. 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 ride control 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.