Efficient Oil Spill Confrontation by Innovative EU-MOP Units

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Abstract

The paper presents the design of an innovative, autonomous oil-skimming catamaran unit developed within the EU-MOP (Elimination Units for Marine Oil Pollution) Research Project, funded by the European Commission (FP6). The aim of the project is the design and validation of the concept of autonomous EU-MOPs, capable of mitigating and eliminating the threat arising from oil spill incidents. The confrontation of the entire spill requires a swarm of such units; the latter corresponds to a major innovative aspect of the EU-MOP scheme, offering an array of favourable characteristics, like scalability, redundancy, fault-tolerance etc.

The special operational features required for the units in order to fulfil adequately their missions resulted in designs with unique hullform properties, deviating from ordinary hullforms and arrangements. The design characteristics and general arrangement, the energy source and propulsion system, the artificial intelligence package, the robotics and the oil processing systems, the structural design and the hydrodynamic performance of the units are presented in the paper.

Keywords

EU-MOP; Catamaran; MonoCat; Oil skimming device; Oil spill response

1. Introduction

EU-MOP is the acronym for Elimination Units for Marine Oil Pollution project, supported by the European Commission under the Sustainable Development, Global Change and Ecosystems thematic area, Sustainable Surface Transport Programme of the 6th Framework Programme. The primary target of the project is the design and proof of concept of autonomous EU-MOPs, capable of mitigating and eliminating the threat arising from oil spill incidents. The units have to be affordable in cost, possibly recyclable, autonomously driven vessels/drones. They will be released in the oil spill area, track the oil concentration specifics of the spill using proper sensors and apply mechanical countermeasures locally. A swarm of such units is required for the confrontation of the entire spill. Different sizes of such units are designed in order to handle the variety of locations where oil spills could occur, ranging from open ocean to harbour or coastal areas. The list of potential users includes port authorities, government agencies (coast guard) and private companies. The complete integrated system including communication, logistical support and response management (Ghonis, 2007) is analysed and assessed.

The successful design of the EU-MOP units is a decisive part of the overall EU-MOP concept development. The objective is to develop the best feasible Elimination Units within the design space defined by the requirements and the constraints of the EU-MOP concept. In this paper the design features of the units will be presented.

2. Background

The EU-MOP design requirements were defined by its mission targets, namely the confrontation of seawater oil spills. These have been defined by formulating appropriate oil spill scenarios. In the context of the EU-MOP units, they have been classified in three groups (Kakalis, 2005). The corresponding scenario characteristics are summarised as follows:

Type of sea area: Open ocean area (sea type I), enclosed seas (sea type II, e.g. the Mediterranean Sea) and shallow water areas (type III, e.g. estuaries, rivers, lakes, ambers, inlets).

Quantity: Small spills (less than 7 tons of oil), medium size spills (7 to 700 tons) and large spills (>700 tons).

Type of oil: Two basic types of oil were being examined: light oils (non persistent like diesel oil) and persistent oils (heavy fuel oil or crude oil).

Meteorological conditions: The variations on the wave height have been taken into account in the type of sea area. A working hypothesis for the EU-MOPs is to be operational 50% of the time on the winter season, which roughly represents 75% of the time year round, is used.

Considering the above classification oil spill conditions, three working hypotheses have been identified for the size of EU-MOPs:

- large model (L) for open ocean type I, with assumed operational limits wave height <2m, wind speed 25 knots (force 6B)
- medium model (M) for sea type II, that has the approximate size of a skimmer head
- small model (S) for a response area of type III designed to operate in very shallow waters.

The available technical solutions for a number of candidate unit's subsystems were analysed, namely their hull geometries, their oil recovery and storage capabilities, the electronics outfit, the propulsion systems, energy source systems and the construction materials. Based on the performed analysis, the applicability of two different hull geometries had been identified:

- a "MonoCat" concept developed by Bureau d'Etudes Mauric (BEM) shown in Fig. 1, and
- a catamaran concept developed by NTUA-Ship Design Laboratory (SDL) shown in Fig. 2.

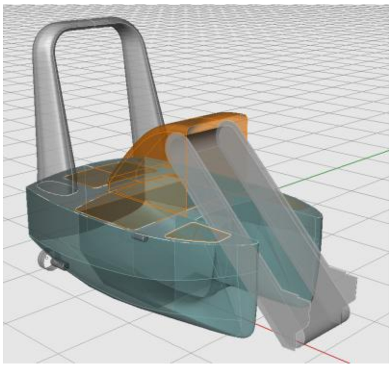

Fig. 1: MonoCat unit

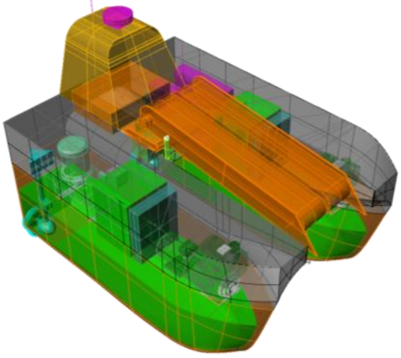

Fig. 2: Catamaran Unit

3. General architecture

The critical requirements defining the design space boundaries were (Lemesle 2005; Ayaz 2006):

- The transportation of the units using 20ft and 40ft containers.
- The speed requirement of 4kts for both the large and the medium-sized units.
- The required recovered oil capacity of $2m^3$ and $1.4m^3$ for the large and the medium unit, respectively.
- The installation of the oil skimming device high on unit's deck.
- The optimization of the main dimensions (length, beam and total height) with respect to the internal arrangement, the propulsion, the stability and the manoeuvring performance.

A trade-off analysis was performed on both hullforms (MonoCat and Catamaran) for the selection of the main dimensions.

3.1 Large Unit

3.1.1 MonoCat Unit

The MonoCat unit is a hybrid hull concept (Lemesle, 2006). The catamaran fore part has been designed with the idea of integrating the skimmer in its optimum position for a maximized recovery efficiency. It also provides a sufficient volume for the electronic, and part of the hydraulic system integration. The middle and the aft part of the hull provide a large volume, in phase with the highly restricting specifications in terms of payload, energy production, storage and distribution, and propulsion system accommodation. The Π-frame on the aft part is a multi-purpose device. As well as being a "stability guardian", it provides volumes for ventilation duct location and eventually dry exhaust pipes to its top end. It also provides space for fitting electronic sensors and antennas in a protected space from oil spills and oil splashes.

Table 1: Large MonoCat main particulars

Length o.a.	3.50	m
Breadth o.a.	2.30	m
Depth	1.29	m
Height in service condition	3.25	m
Lightship	1692	kg
Deadweight	1572	kg
Displacement, Full load	3264	kg
Oil tank capacity	2.0	m^3
Skimmer type	Lamor LBC 2C-2700	
Speed, max	4.0	kts
Speed, recovery mode	1.0	knot

An important feature of MonoCat is the amidships located $2m^3$ recovery oil tank, which can be removed safely and quickly from the Unit with any lifting device and replaced (by an empty one) within a short period of time. This design feature also allows for an easy cleaning and stacking of the tanks. The general arrangement of the MonoCat unit is shown in Fig. 3. The main dimensions of the large MonoCat unit are given in Table 1 and its hull lines in Fig. 4.

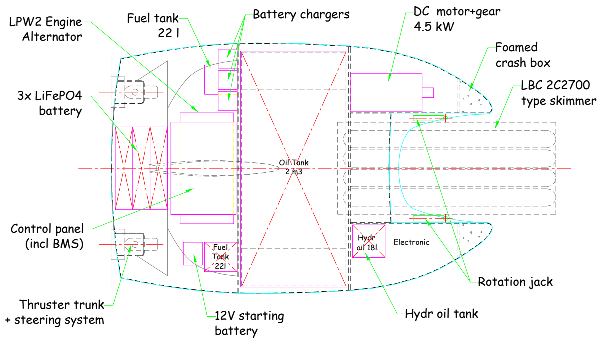

Fig. 3: Large MonoCat plan view

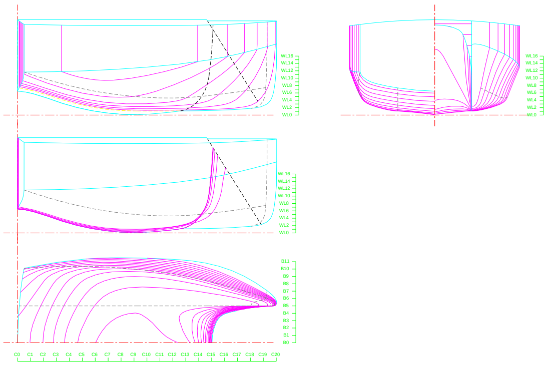

Fig. 4: Large MonoCat hull lines

The unit uses a hybrid energy pack for achieving a 24 hours autonomy. It is comprised of a diesel-electric part and a battery pack. The diesel engine is the water cooled Lister Petter LPW2 which outputs 5.5 kW (Armaoglu, 2007). It has a dry exhaust which is located in the mast. The unit is equipped with 4 $LiFePO_4$ battery banks. Their capacity is 2.25 kWh each. The resulting autonomy of the system is 24 hours. The large MonoCat unit uses 2 DSSI 2100 azimuth DC thrusters capable of delivering 34kg of thrust. These propel the unit to a maximum speed of 4kts.

3.1.2 Catamaran Unit

For the catamaran several combinations of length, demihull breadth and resulting demihull clearance were considered for given draught and displacement (Boulougouris, 2006). They were compared on the basis of the resulting resistance and effective horse power characteristics. The resistance of each demihull at the preliminary design stage was first estimated using Holtrop's method (Holtrop, 1982; Holtrop 1984). Using the general particulars of the best candidate and considering that the hullforms of high-speed multihulls are simple shapes (Lamp, 2004), a set of lines was generated by NAPA (Napa Oy, 2005) with a limited number of points. This permitted the easy iteration of the hull's geometry until the target properties (e.g. volumes, volume centres etc.) were achieved. The main particulars of the Large Catamaran Unit are given in Table 2. In Fig. 5 its hull lines are shown.

Based on the selection of the various equipment parts a 3D model (see Fig. 6) and a weight breakdown spreadsheet were created. These permitted the exact weight allocation for the trim and stability at the various loading conditions, and the check of the adequacy of volume for all parts. The convergence of this process provided the final layout of the unit.

Table 2: Large Catamaran main particulars

Length o.a.	3.20	m
Breadth o.a.	2.30	m
Depth	1.45	m
Hull Separation	1.625	m
Tunnel breadth	0.950	m
Lightship (incl. 12% growth margin)	1514	kg
Deadweight	2048	kg
Displacement, Full load	3562	kg
Oil tank capacity	2.0	m^3
Skimmer type	Lamor LBC 2C-2700	
Speed, max	4.0	kts
Speed, recovery mode	1.0	knot

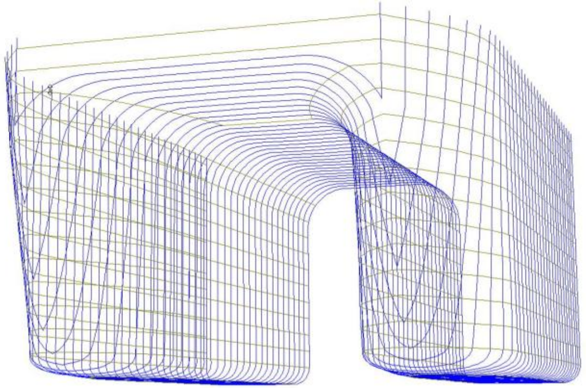

Fig. 5: Large Catamaran hull lines

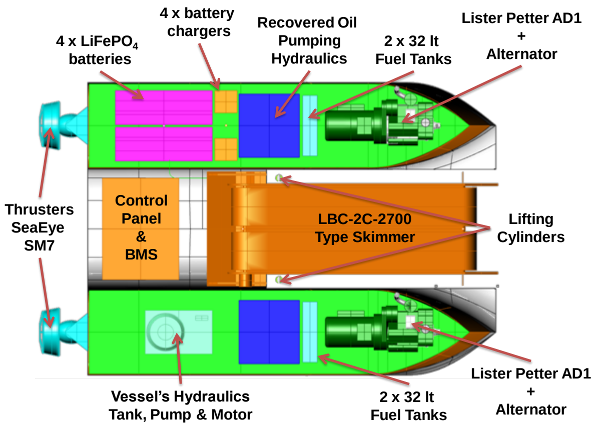

Fig. 6: Large Catamaran plan view

3.2 Medium Unit

3.2.1 MonoCat Unit

The medium size MonoCat unit is similar to the large one. The main difference is the recovered oil capacity that in this case is limited to 1.25 m^3. This results in the smaller main dimensions given in Table 3.

The medium MonoCat unit uses the same hybrid energy pack as the large MonoCat unit (Armaoglu, 2007). It is propelled by 2 DSSI 2100 azimuth DC thrusters capable of delivering 22kg of thrust. These propel the unit to a maximum speed of 3 to 4kts. Its service speed is 0.7kts. The general arrangement of the unit is shown in Fig. 7. The main dimensions of the medium MonoCat unit are given in Table 3 and its hull lines in Fig. 8.

Table 3: Medium MonoCat main particulars

Length o.a.	2.40	m
Breadth o.a.	1.88	m
Depth	1.20	m
Height in service condition	2.67	m
Lightship	1096	kg
Deadweight	1075	kg
Displacement, Full load	2171	kg
Oil tank capacity	1.25	m^3
Skimmer type	Lamor LHS 2CP	
Speed, max	4.0	kts
Speed, recovery mode	0.7	kts

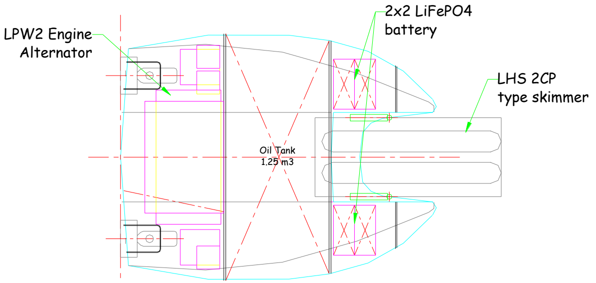

Fig. 7: Medium MonoCat plan view

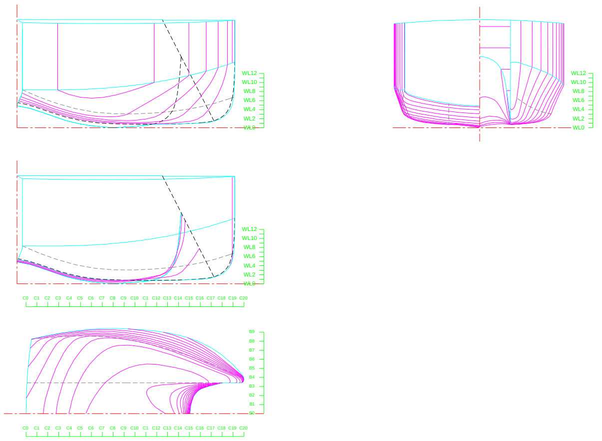

Fig. 8: Medium MonoCat hull lines

3.2.2 Catamaran Unit

For the medium size catamaran unit, the same procedure as for the large one was used. Starting with the requirements produced by the EU-MOP operational concept for this size of units, a trade-off analysis was performed for the selection of the main particular. The main characteristics of the developed hullform are given in Table 2. A wireframe of cross sections and waterlines is shown in Figure 4. The energy plant is the same as for the large Catamaran unit with the only difference that the number of batteries has been reduced to 2~3 banks (Armaoglu, 2007).

The two Catamaran units can be compared in Figure 6. It is important to note that even though the oil carrying capacity was reduced by 30% when moving from the large to the medium size design, the rest of the particulars changed as follows:

• Length	-7%
• Breadth	-18%
• Draught	-14%
• Full Displacement	-28%

Table 4: Medium Catamaran main particulars

Length o.a.	3.00	m
Breadth o.a.	1.88	m
Depth	1.25	m
Hull Separation	1.28	m
Tunnel breadth	0.68	m
Lightship	1151	kg
Deadweight	1431	kg
Displacement, Full load	2582	kg
Oil tank capacity	1.4	m^3
Skimmer type	Lamor LHS 2CP	
Speed, max	4.0	kts
Speed, recovery mode	0.7	knot

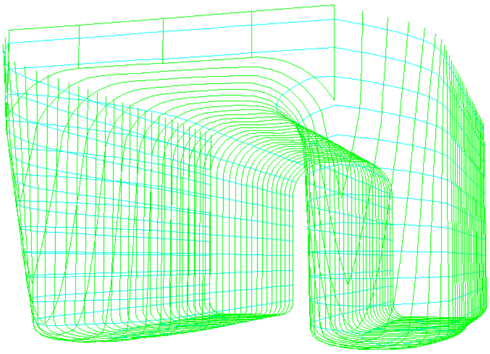

Fig. 9: Medium Catamaran hull lines

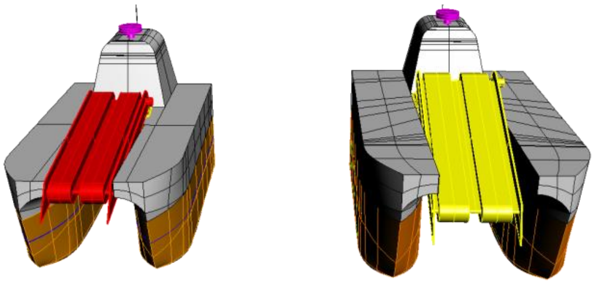

Fig. 10: Comparison of the Medium and Large units

3.3 Small Unit

The small size unit, developed by BEM, is very innovative and unconventional. Designed for type III response area, it is capable to operate in very shallow waters. Its recovered oil capacity is 0.20 m^3. This results to significantly smaller main dimensions as given in Table 5.

Table 5: Small MonoCat main particulars

Length o.a.	1.20	m
Breadth o.a.	1.10	m
Depth	0.70	m
Lightship	235	kg
Deadweight	190	kg
Displacement, Full load	425	kg
Oil tank capacity	0.20	m^3
Skimmer type	Ro Clean – DBD 5	
Speed, max	1.0	kts
Speed, recovery mode	0.5	kts

The small EU-MOP unit uses batteries as its sole energy source. One or two banks of $LiFePO_4$ batteries provides enough power for achieving a maximum speed of 1 knot using two fixed DC thrusters. Its service speed is 0.5kts. Its autonomy is around 4 hrs minimum. The general arrangement of the unit is shown in Fig. 11.

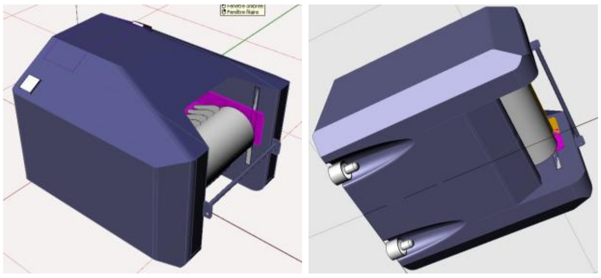

Fig. 11: **Small EU-MOP unit**

4. Resistance

The resistance of the various models was initially calculated numerically and then model tests were conducted in order to verify the numerical estimations.

4.1 Numerical results

The resistance of the various models was initially calculated by SIREHNA with the software REVA, which uses a Boundary Elements Method based on Rankine sources (Lemesle, 2006). The resistance calculations were performed for both the full load and the lightship conditions. The first investigated condition was decisive for sizing the propulsion plant. The resistance curve for speeds from 1 to 5 kts, for both large units (MonoCat and Catamaran), is shown in Fig. 12. The wave field for the full loaded units running at 5 kts is depicted in Fig. 13 and Fig. 14, respectively for the Large MonoCat and the large Catamaran unit.

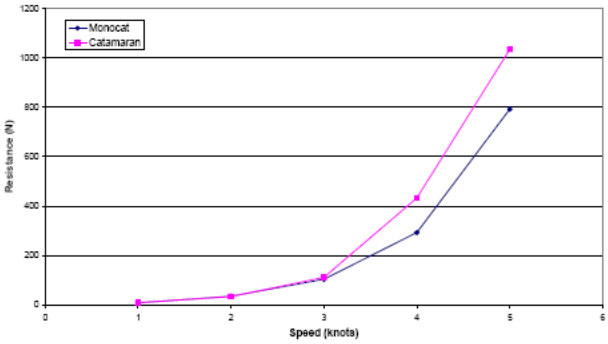

Fig. 12: **Resistance curve for both large units acc. to numerical calculations**

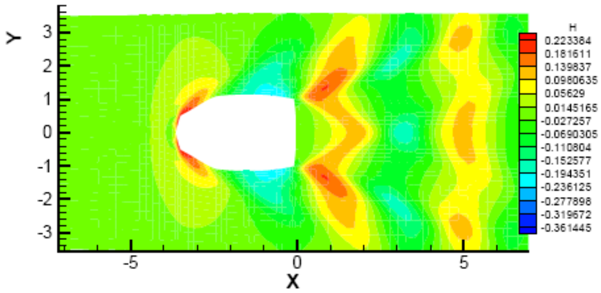

Fig. 13: **Wave field of the large MonoCat at full load condition running at 5 kts**

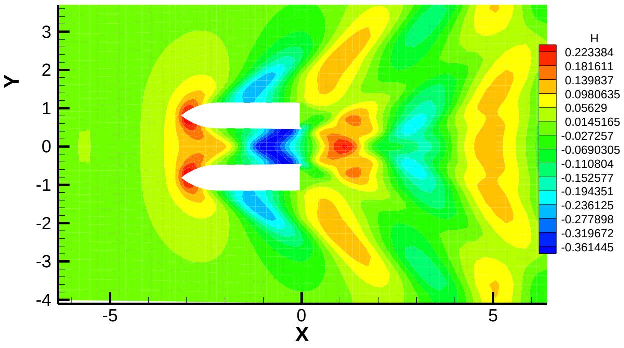

Fig. 14: **Wave field of the large Catamaran at full load condition running at 5 kts**

Similar calculations were performed for the medium-sized units and the small EU-MOP unit.

4.2 Model Tests

Two sets of resistance model tests were performed in two different Model Basins. At the Centre for Marine Hydrodynamics of the Universities of Strathclyde and Glasgow, UK, the Large MonoCat EU-MOP unit was tested, while the Large Catamaran unit was tested at the Laboratory of Ship and Marine Hydrodynamics at the National Technical University of Athens, Greece (Boulougouris, 2007). The MonoCat's model constructed was of scale 1:3 (see Fig. 15) to the relevant full size EUMOP unit. It was tested in 4 different conditions, comprised of two loading conditions, namely full load and lightship, and two operating conditions, one with brush in the oil skimming position and one with the brush in the upper position (transit mode). The Catamaran model's scale ratio was 1:2 (see Fig. 18). For the Catamaran the full load condition was tested at various speeds, using different turbulence stimulators. The analysis of the results revealed the following:

- Large turbulence occurred at the transom of the units at higher speeds creating a very difficult problem even for the most advanced CFD codes.
- The agreement of the numerical calculation and the model test measurements was significantly better for the MonoCat (see Fig. 17) than for the catamaran (see Fig. 18).
- The MonoCat model proved its ability of accumulating oil at its operational speed.
- At the transit speed of 5 knots the dynamic suction of the MonoCat model was considerable, while the Catamaran model's dynamic sinkage at the same speed was significantly less.
- The Catamaran model on the other hand presented significant dynamic trim at 5 knots.
- Both models created a large wake at 5 knots which could disrupt the oil accumulation process of the rest of the swarm.
- The tests conducted with the Monocat model's brush at its oil skimming position have shown that its effects are minimal to the overall resistance at the operational speed.

Fig. 15: Large MonoCat model with its brush

Fig. 16: Large Catamaran model in the towing tank

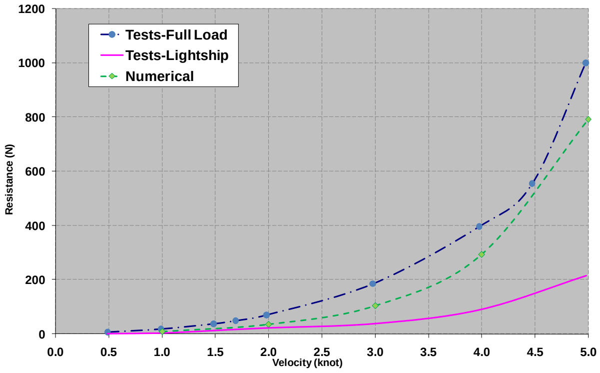

Fig. 17: Full scale resistance of large MonoCat unit

The performance characteristics of both models indicated that the transit speed should be limited to 4 knots for better operability. Benefits include better environmental impact and significant reduction of the power requirements.

4.3 CFD calculations with oil films

Extending the vessel's resistance estimations to account for phenomena that cannot be included in standard towing tank experiments, the University of Oxford performed a series of CFD calculations for the large catamaran assuming an oil film on the water surface (Armaoglu, 2007). The main idea is to estimate the increased resistance caused by navigating through the oil film.

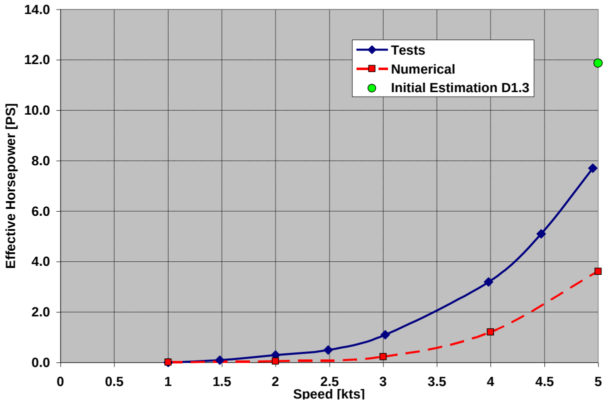

Fig. 18: Full scale effective horsepower of large Catamaran

The generated hybrid grid of the domain consisting of 1,346,747 elements is shown in Fig. 19. The mesh is structured on the hull and its vicinity and unstructured elsewhere and for the discretisation the Gambit v.2.2.30 (Fluent, 2007) software was used.

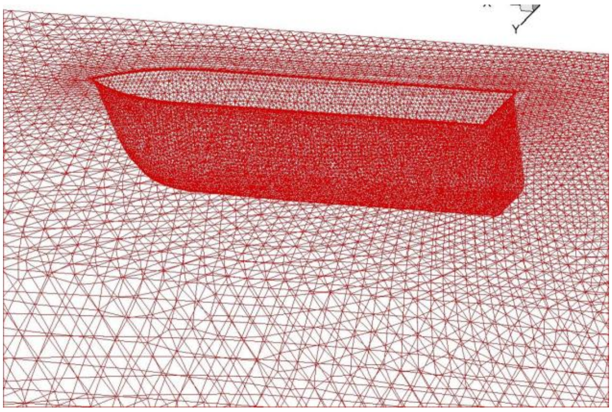

Fig. 19: Grid generated for the large catamaran unit

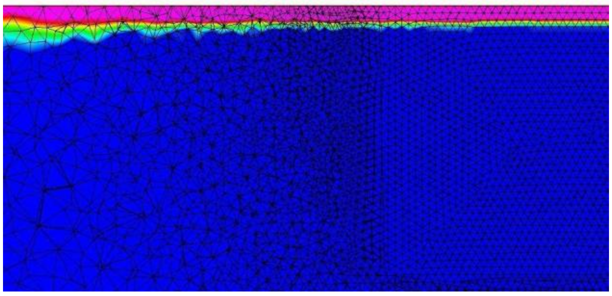

Fig. 20: Grid generated for the EU-MOP vessel flowing through a two-layer liquid

At the top of the sea surface a film of oil was assumed with density 950 kg/m^3 and (initial) dynamic viscosity of 2.324 kg/m-s. It is worth noting that the corresponding viscosity for the seawater is 0.0010735 kg/m-s. The oil film has a thickness of approximately 5 cm (see Fig. 20).

The computational model was implemented in the CFD-ACE+ platform (ESI Group, 2007) where a two-layer k-ε turbulence model was assumed. It was ensured that the near-wall resolution used led to a $y+$ of approximately 1. This turbulence model splits y in two sublayers: the outer layer employs the standard k-ε turbulence model to account for turbulence effects due to the high Reynolds number (Re~7.8×10^6), and the inner uses an one-equation model to account for viscous effects. The numerical solution of the CFD model derives the velocity and pressure fields around the EU-MOP catamaran unit, as shown in Fig. 21.

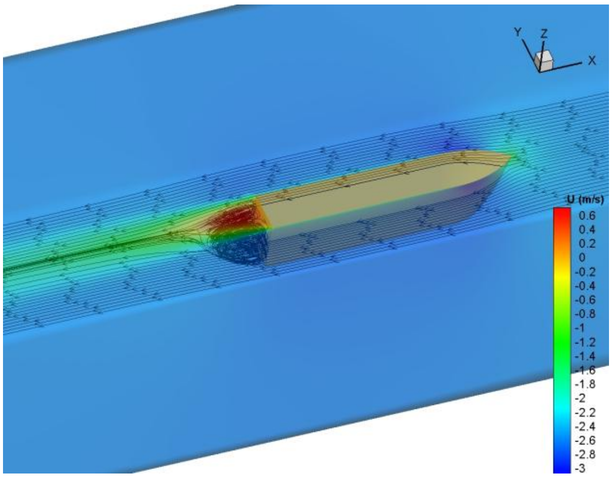

Fig. 21: Velocity magnitude and flow field in the catamaran unit

The study performed for catamaran unit assumed a speed of 4 knots. Starting from fresh-oil conditions, the viscosity was increased from 5 cm film up to 10 times (i.e. up to 23.24 kg/m-s). This resulted to a maximum resistance increase due to oil film viscosity effects of 21.5%.

5. Hydrostatic Stability

Calculations were performed for three loading conditions (1=lightship, 2=50% loaded, and 3=fully loaded) and two brush positions (flat or inclined). The hydrostatic characteristics were investigated by SIREHNA using the software Hublot, a numerical tool developed by IFREMER for hydrostatic stability calculations. The data outputs are the equilibrium and associated hydrostatic characteristics: righting arm GZ, hydrostatic curves, etc. These curves make it possible to calculate stability criteria related to regulation, such as the area under GZ curve between 0 and 30 deg of heel or the angle of maximum righting arm.

5.1 Large units

The employed stability criteria and the attained values by the large MonoCat are given Table 6. The relevant values for the large Catamaran are given in Table 7.

5.2 Medium units

The stability criteria and the attained values by the medium MonoCat are given Table 6. The relevant values for the medium Catamaran are given in Table 9.

5.3 Wind and wave effects

The calculations for the wind and wave effects on the EU-MOP units were performed only at lightship condition because these were identified as the critical ones; moreover, only inclined brush position is used because at this condition the wind arm lever is the highest. The calculations were performed according to the Recommendation of Les Affaires Maritimes in Appendix 211-1.A.3 (weather criterion) requiring the area b in Fig. 22 to be larger than area a.

Table 6: Stability of large MonoCat unit

		A(0,30°) (m.rd)	A(0,40°) (m.rd)	Gzmax (m)	Teta Gzmax (deg)
Light	Flat	0.044	0.074	0.173	35
	Inclined	0.059	0.100	0.240	40
50% loaded	Flat	0.067	0.112	0.264	40
	Inclined	0.087	0.147	0.361	40
Fully loaded	Flat	0.068	0.103	0.209	30
	Inclined	0.096	0.152	0.326	40
Criteria		**>0.055**	**>0.09**	**>0.2**	**>25**

Table 7: Stability of large Catamaran unit

		A(0,30°) (m.rd)	A(0,40°) (m.rd)	GZmax (m)	Teta GZmax (deg)
Light	Flat	0.152	0.217	0.478	25
	Inclined	0.164	0.238	0.516	25
50% loaded	Flat	0.118	0.216	0.625	40
	Inclined	0.127	0.233	0.670	40
Fully loaded	Flat	0.096	0.168	0.446	60
	Inclined	0.103	0.180	0.489	60
Criteria		**>0.055**	**>0.09**	**>0.2**	**>25**

Table 8: Stability of medium MonoCat unit

		A(0,30°) (m.rd)	A(0,40°) (m.rd)	GZmax (m)	Teta GZmax (deg)
Light	Flat	0.041	0.067	0.157	40
	Inclined	0.059	0.100	0.249	45
50% loaded	Flat	0.047	0.082	0.223	45
	Inclined	0.059	0.103	0.290	50
Fully loaded	Flat	0.027	0.046	0.109	40
	Inclined	0.037	0.062	0.155	45
Criteria		**>0.055**	**>0.09**	**>0.2**	**>25**

Table 9: Stability of medium Catamaran unit

		A(0,30°) (m.rd)	A(0,40°) (m.rd)	GZmax (m)	Teta GZmax (deg)
Light	Flat	0.085	0.128	0.293	30
	Inclined	0.094	0.144	0.328	30
50% loaded	Flat	0.075	0.141	0.446	45
	Inclined	0.080	0.150	0.474	45
Fully loaded	Flat	0.067	0.121	0.362	70
	Inclined	0.071	0.128	0.390	70
Criteria		**>0.055**	**>0.09**	**>0.2**	**>25**

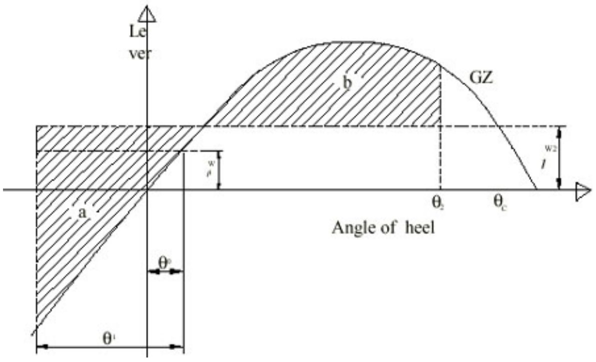

Fig. 22: Weather criterion definition

The steady wind heeling lever is a function of the wind speed which in this case for Douglas Scale Sea State 4 was assumed 20 kts. The ratio b/a for each unit is presented in Table 10.

Table 10: Weather criterion b/a ratio

	Large		Medium	
	Mono	Cat	Mono	Cat
b/a ratio	1.36	1.16	1.23	1.17

Obviously both units satisfy the weather criterion requirement for b/a>1.

6. Seakeeping

Motion transfer functions were calculated at units' CoG with the software AQUA+ (SIREHNA, 2007), which is based on a 3D radiation - diffraction method using Kelvin sources. The criteria for the behaviour of the units are the limitation of motions for brush efficiency. The seakeeping calculations parameters were (Lemesle, 2006):

- Two speeds, 1 and 5 kts for the large units, 1 and 4 kts for the medium units
- Five headings, 0 to 180 deg with 45 deg step
- Three loading cases, departure condition with empty recovered oil tank, 50% load condition with the recovered oil tank half full and the arrival condition with the recovered oil tank full
- Two brush positions, flat and inclined.

Statistical values of motions at CoG and relative brush tip position/sea surface were calculated for 4 sea states (1, 2, 3 and 4). The significant wave height H_S and the peak period T_{peak} for each sea state is given in Table 11.

Table 11: Seakeeping calculation Sea States

Sea State	1	2	3	4
Hs (m)	0.05	0.30	0.88	1.88
T_{peak} (s)	2.0	7.5	7.5	8.8

The T_{peak} value for sea state 1 was chosen close to the roll period of the unit in order to have a dimensioning value. Since inertia (gyration) radius data were not available and since no classical formulas could be used to estimate their value, relevant data for the EU-MOP units were estimated using a module of AQUA+ software which assumes that the weight is equally distributed over the wetted surface of the hulls.

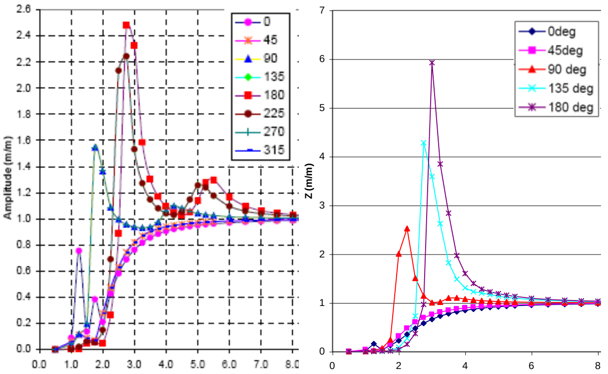

Fig. 23: Heave RAOs at full load of the large MonoCat (left) and Catamaran (right), running at 5kts

Indicative results for the large MonoCat and Catamaran units are shown in Fig. 23. The analysis for the location of the oil recovering brush tip has shown that (Lemesle, 2006):

- For the large unit, the RMS value of the relative position of brush tip to the sea surface is almost always negative (tip submerged) which ensures the proper function of the oil recovering device.
- For the medium unit, only in the lightship condition, the brush tip is almost constantly above sea water. This could pose a problem of the initiation of the oil recovery. However, this is not a real operating condition because the unit has no fuel. The addition of even a small fuel weight (for few hours' operation) will alleviate this problem.

7. Energy Plant, Propulsion and Steering

Evaluation of the energy plant and the propulsion system was made by SSRC (Armaoglou, 2007), considering the initial and lifecycle costs, system reliability and performance, maintenance and manpower requirements, as well as vessel arrangement options. The mission profile of EU-MOP units is closer to a dynamically positioned vessel rather than a conventional sea-going ship; therefore, the design of the EU-MOP unit propulsion system must be made with this in mind. For such a mission profile, the propulsion system must be able to generate counter forces against environmental ones such as wind, current and waves. Environmental forces are omni-directional, therefore, propulsion and steering system or devices must have the ability to perform station keeping operations under these conditions. The propulsion system must also be able to generate enough power in longitudinal direction to move the vessel from location to location.

7.1 Energy systems

All large and medium EU-MOP units are powered by a diesel power with a back up battery supply. This battery supply is used for standby in the event of engine breakdown as well as supplement power during normal operations. The operating principle of a battery-powered hybrid vehicle (HV) is straightforward. There is an energy storage device located on the vessel supplying energy in the form of electricity to the propulsion system and possible other plant. This is done via an electric conversion system depending on whether the output supply is AC or DC.

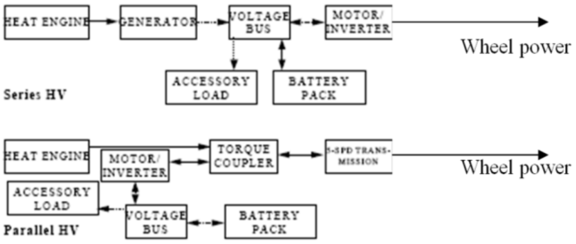

Fig. 24: Series HV vs. Parallel HV

There are two different methods in a hybrid energy system which can supply energy to the vessel's power plant:

- Series system HV
- Parallel system HV

The two systems are in stark reality to the standard genset system and the schematic in Fig. 24 illustrates this difference.

The series HV system as applied to a floating vessel would be similar to Fig. 25, where clearly there would be a constant battery input and the battery chargers (there will be a number of battery chargers incorporated within the Lithium Phosphate battery system) would be in constant use. Considering the demands of the EU-MOP units, the parallel HV system allows the batteries to be used to a lesser degree. This reduces the possibility of the batteries overheating with constant use whilst at the same time increases battery life. Battery energy provides a portion of the energy for unit's motive power in certain high sea currents conditions as well as acting alone at times where the diesel engine fails or is shutdown for other reasons (e.g. high hydrocarbon atmosphere percentage conditions). When propulsion power is low the charging of the batteries allows the engine loading to be increased and optimised in order to maintain high operating efficiency.

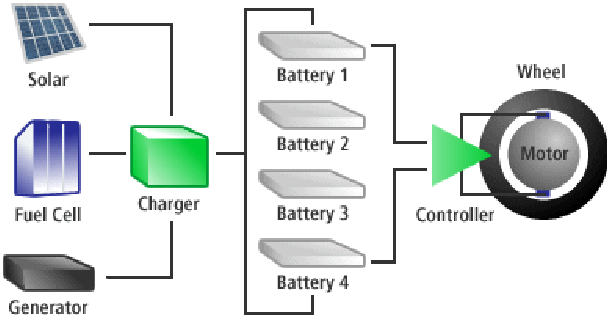

Fig. 25: A battery charging system – with constant battery use

The diesel engine genset will provide sufficient power for the operation of the vessel for 24 hours and the size of this plant has been determined for the different EU-MOP vessels. The genset loadings will be maintained approximately 75 to 80%MCR to prevent increased lubrication oil consumption and subsequent glazing of the diesel engine's cylinders. In this parallel HV system the propulsion motor (PM) and the genset (sometimes called the Auxiliary Power Unit, APU) are both connected electrically inline. The system can be configured such that the APU powers the unit's systems while simultaneously recharging the energy storage system. The parallel-hybrid configuration can be designed in either an engine-dominant or a battery-dominant subtype.

The principal components of the EU-MOP unit energy system include: a drive motor, a controller and inverter, an energy storage device, a genset and other auxiliary systems, such as cooling and ventilation system, the propulsion motors. The speed of the PM is controlled by an on-board electronic controller.

The APU selected for the MonoCat units (large and medium is the Lister Petter LPW2 (shown in Fig. 26) while for the Catamaran units the Lister Petter AD1, shown in Fig. 26 (normally aspirated) and air cooled diesel engine was selected.

Fig. 26: Lister Petter LPW2

Fig. 27: Lister Petter AD1

7.2 *Propulsion*

Two primary types of electric motors can be used in electric vehicles: direct current (DC) motors and alternate current (AC) motors. On a power comparative basis, an AC motor generally exhibits a higher efficiency, has a favourable power to size/weight ratio and is less expensive than a DC motor. AC motors require an inverter and more expensive controller, increasing the associated cost. An electric vehicle power train design based on a DC motor may be slightly less efficient overall and DC motors themselves are much more expensive. However, the controllers for DC motors are generally less expensive making the total cost compare between the two types of motors. DC motors have excellent speed characteristics.

The PMs selected for the EU-MOP units after consideration of a large number of alternatives were the AC powered Deep Sea Systems Incorporated (DSSI) 2100 for the MonoCat designs (see Fig. 28) and the DC powered SeaEye SM7 for the Catamaran designs (see Fig. 29). All motors have their starters housed within the MCP. These starters are accompanied with the appropriate motor protection and line fuses.

7.3 *Steering*

A steering column was used in all units. For the MonoCat it is located in the hull, while for the Catamaran it is located outside the hull. Each of the steering column connection units is universal in design, application and interchangeable with every thruster, no matter the power or mass of the propulsion system. It is a resilient and robust steering system that resists propeller upthrust and at the same time is able to safely support the mass of the unit whilst combating the variation in propeller load.

Locating the propeller under the after hull in the conventional manner was inappropriate as experience has shown it is better to initiate a "swing transfer" of an all-in-one replacement unit when required and accordingly, in such circumstances, the propeller and its steering column must be in a position where it can be easily removed.

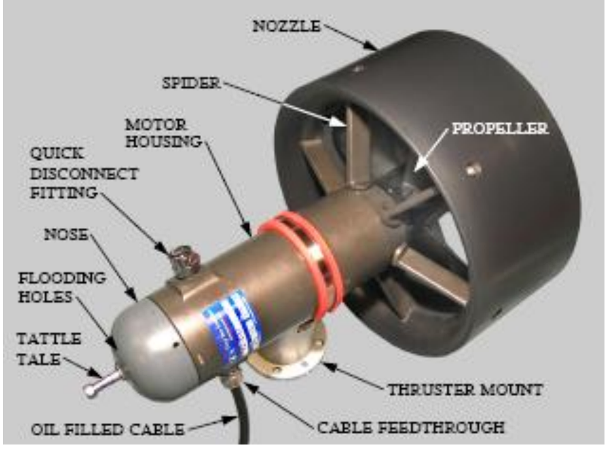

Fig. 28: **DSSI 2100–AC motor used on the MonoCat**

Fig. 29: **Seaeye SM7–DC motor used on the Catamaran**

The Catamaran units have their propeller and steering column located outside the hull thus avoiding hull penetration(s) under the waterline and this gives two further advantages as follows:

- Avoidance of taking the boat out of the water to remove the propeller for repair or replacement.
- Any damage to the propeller hub by collision or rope entwinement will not cause damage to the hull and leaks or a substantial ingress of water.

The Column Steering Connection unit (CSC) is shown in Fig. 30. The column steering connection unit is screwed on to the end of a column that is clamped onto the stern on the hull via a 3" BSP screwed connection at the top end of the drawing The steering column and the CSC during fitting procedures will be able to hang on supports bolted on to the hull whilst locking clamps firmly hold the column in place (this will be illustrated later). The CSC is locked in place after it is screwed on to the column by a 3/8th" BSP grub screw. Internally, as can be seen in Fig. 30, the CSC has a sealed thrust race and a Teflon or needle bearing that are preloaded by the Bearing Retention Ring. Once the bearing is loaded to the satisfaction of the technician attending another 3/8th" BSP grub screw will lock the Bearing Retention Ring into place to prevent the ring coming loose during steering operations. Of the two options the needle bearing offers the best solution.

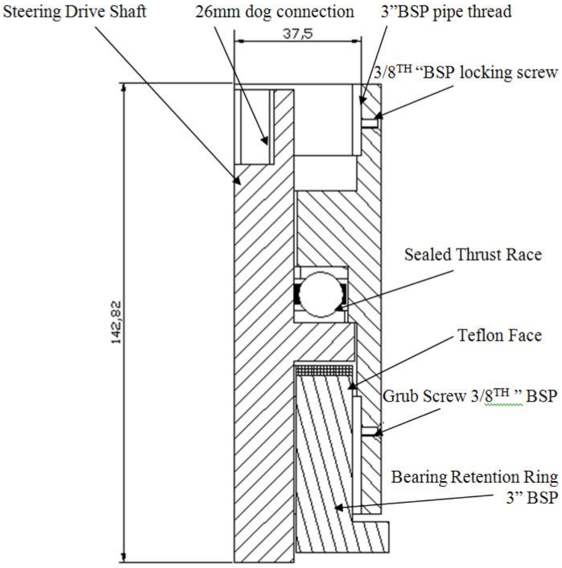

Fig. 30: **Column Steering Connection (CSC) unit**

8. Manoeuvring

For the assessment of the manoeuvring performance of the units, the IMO regulations were considered as a guideline. For the analysis of the stopping ability and speed control in deep water, IMO recommends the "crash-stop" manoeuvre which is mainly a test of engine functioning and propeller reversal. The stopping distance of the ship is of importance and recorded during this manoeuvre. "Time to dead in water" is realised in a stop engine-full astern manoeuvre performed after a steady approach at full test speed.

For the assessment a manoeuvring mathematical model was used by SSRC (Armaoglou, 2007) in order to perform computer simulations of the manoeuvring characteristics of EU-MOP units. The operational requirements of the EU-MOPs require a high manoeuvrability standard and since the steering system is not a conventional rudder, the effect at slow speed is of interest. Moving and turning to a direction is achieved by either thruster steering angle deflection or by a change of rpm in one of the thrusters.

The results showed that the catamaran model is much more directionally stable compared to the MonoCat unit. Although the turning characteristics of the catamaran satisfies the IMO regulations, from operational effectiveness view the MonoCat model tends to give better results. In Fig. 31 the effect of the loading condition on the turning ability of the large catamaran unit is shown.

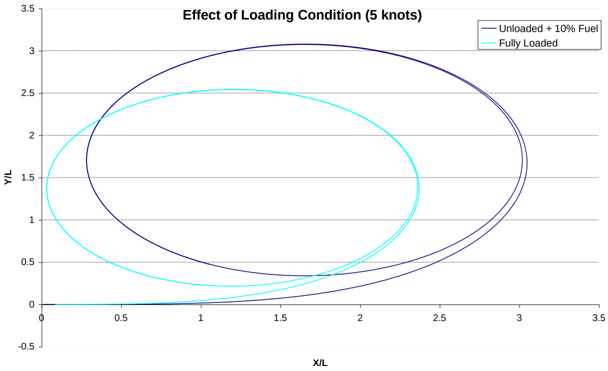

Fig. 31: Effect of loading condition to turning ability for large catamaran unit's speed of 5 kts [14]

9. Electronics

Four sensor configurations were investigated for the Large and Medium units. Among those configurations, one that best comply with the various Artificial Intelligence Architecture was selected. It is comprised by the following sensors for the Large and Medium EU-MOP units (Fritsch, 2006):

- a DGPS system,
- an obstacle detection and collision avoidance system,
- a depth sensor,
- a compass,
- an oil in water sensor,
- level indicators for the fuel tank and the oil storage tank,
- a radio-based communication system,
- an embedded control processor / computer.

10. Oil skimming device

Both large units are equipped with the Lamor LBC 2C-2700 oil skimming device shown in Fig. 32(Campos, 2007). It is based on the chain brush technology and is claimed to offer high performance and simple operation for near shore and harbour oil spill recovery operations. This type of equipment is originally designed to be mounted on a vessel and the manufacturer presents the equipment has an effective tool at vessel speeds of 1-3 knots.

For the medium size units the Lamor LHS 2CP was selected (see Fig. 33). It is a small skimming system conceived to recover extremely high viscous oil, emulsion, and bitumen. The LHS is designed to collect these heavy materials floating on the water surface or submerged below the surface and feed the oil into a Lamor Archimedes screw pump. A mechanical feeder skimmer lifts or drags the oil out of the water to a position above the water surface, and feeds or drops it into a collection tank or a transfer pump. The LHS 2 CP can also confront other types of oil just by replacing the oleophilic brush belt with another one more adapted to a wider range of oils.

For the small unit the Ro Clean – DBD 5 (Disk-brush Drum, see Fig. 34) was considered to be the best option for the EU-MOP concept. It is a skimmer for industrial, harbour and coastal water applications. According to the manufacturer the DBD is able to operate in a wide range of oils, from light to heavy. This model is also capable of operating either with disk banks or brush drums. The Drum-Brush inserts are available to enhance heavy oil recovery, with the units being slipped in and out of the skimmer head. The manufacturer offers several configurations – single, twin or triple banks of rotating oleophilic discs.

Fig. 32: Lamor Bow Collector 2 C2700

Fig. 33: Lamor LHS 2 CP

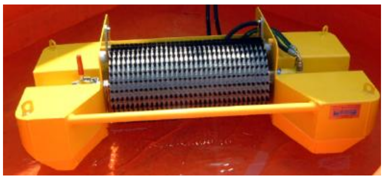

Fig. 34: Ro-Clean DBD 5

11. Structural design

The structural design of the units was performed by SSRC (Khalid, 2007). Two materials were identified as applicable for the units, namely FRP and aluminium alloy. Due to non-existence of specific design rules or regulations, the global structure design of the two novel hull forms, MonoCat and Catamaran, was carried out using the FEA software ANSYS Workbech^{TM}. Aluminium scantlings are designed using Aluminium alloy 5083, while E-glass Woven Roving reinforced by the polyester resins is used for the Fibre Reinforced Plastic (FRP) Units. Optimisation of shell plate thicknesses, stiffener sizes and stiffener spacing was carried out using the Design of Experiment feature of ANSYS Design Explorer. The results have shown that the FRP designs are more promising on both the structural lightness and structural strength point of view. In Fig. 35 the main hull stiffener disposition of the large MonoCat built with FRP is shown. In Fig. 36 the equivalent (von-Mises) stress distributions on the large Catamaran unit are depicted while the unit is lifted out of water for offloading the skimmed oil to mother vessel.

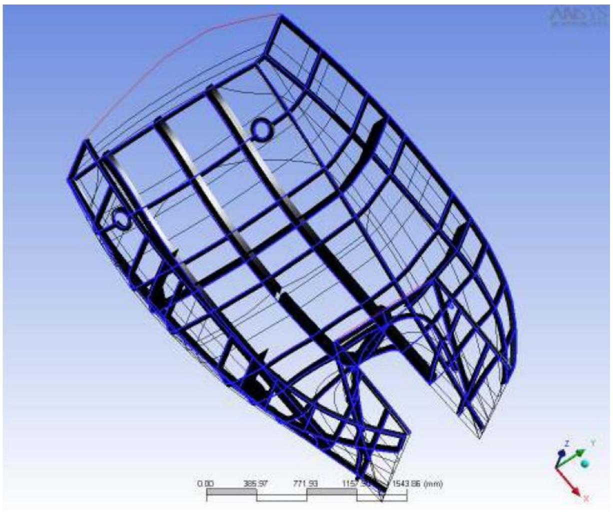

Fig. 35: FRP Unit Main Hull Stiffener Disposition of the Large MonoCat

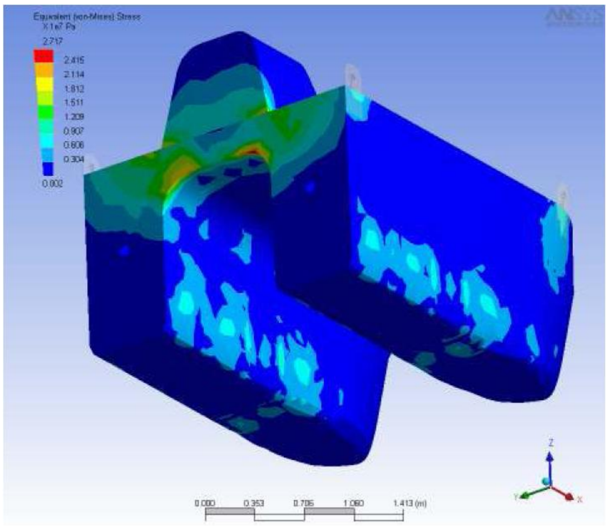

Fig. 36: Equivalent (von-Mises) stress distribution on large Catamaran

12. Conclusions

The design of a set of autonomous oil-skimming units, developed within the EU-MOP (Elimination Units for Marine Oil Pollution) Research Project funded by the European Commission (FP6, Contact No. TST4-CT-2004-516221, Duration 2005-2008), has been presented. In particular, the design and performance of different units in size (large, medium, small) that fulfil the set requirements and specifications of the EU-MOP operational concept have been assessed. The system components of the units have been also outlined. The present findings suggest that the ultimate goal of this project to develop efficient, manageable and feasible designs that ensure adequate oil confronting records for the proposed units is achievable. The estimation of the cost of the various units and the overall cost of the integrated system is now underway in order to assess its cost-effectiveness. The next step will be the verification of these findings by the performance of full scale prototype(s), hopefully to be materialised in the near future.

13. Acknowledgements

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