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An investigation into the benefits of reconfigurable hull forms

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Some vessel types, such as warships and motor yachts, are often required to operate efficiently at two different speed zones: low speed cruise; and high-speed sprint. In the past, a single optimised hull form has been developed, with a balance between the different roles, based on the requirement set and on the operations envisaged.

This paper reports on the results from an investigation into the possible advantages of a ship with a reconfigurable hull form, allowing optimisation for each of the two different speeds. This follows on from earlier work (*Int. J. Maritime Engg* **148**) which demonstrated possible improvements in operational efficiency.

The two main improvements demonstrated in the earlier work were due to stern shape reconfiguration and change in propulsor type from waterjet propulsion to an azimuthing thruster. The current work focuses on these areas in more detail.

Resistance experiments were conducted with and without a stern extension at three displacements to determine the influence of increasing the displacement due to the additional mass required for the reconfiguration.

The results were applied to a test case of a Fast Offshore Patrol Vessel, and it was demonstrated that considerable savings in fuel could be possible, depending on the operational profile, and the additional mass required for the reconfiguration.

1. Introduction

Many vessels, such as warships and motor yachts, are required to operate efficiently at two different speed zones: low speed cruise; and high speed sprint.

Historically, a single optimised hull form would be developed, with a balance between the different roles, based on the requirement set and on the operations envisaged. In many cases this would use two different prime mover configurations, one for the low speed and one for the high speed.

The aim of this study was to investigate the possible advantages of a ship with a reconfigurable hull form, allowing optimisation for each of the two different speeds. This work built on a previous study [1] which demonstrated various improvements in operational efficiency.

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The two main improvements demonstrated in the earlier work were due to stern shape reconfiguration and change propulsor type from waterjet propulsion to an azimuthing thruster. These areas were the focus of this work, which provided refined figures for the possible improvements in operational efficiency that could be achieved by reconfiguring in this way.

Other modifications were investigated in the earlier work, including adjustable bulbous bows, and use of both ballast and fuel to change the vessel trim. Neither were considered worth pursuing.

2. Case study

In order to develop the concept in such a way as to investigate its merits, and determine whether the magnitude of the fuel savings warrants the additional first cost associated with a more complex hull design, a case study using an example vessel type was used. It is important to realise, however, that the concept can be applied to other vessel types.

For this purpose an Offshore Patrol Vessel (OPV) was selected, and it was assumed that the two speeds of operation are:

- 15 knots: where most of the time will be spent;
- 40 knots: required for occasional sprint.

For the purposes of this study a 93 metre (LWL) 1,774 tonne base vessel was chosen. It was assumed that this will be propelled by waterjets driven by gas turbines to enable it to reach the required top speed of 40 knots. For the standard, or non-reconfigurable, case it is assumed that twin Diesel engines are used to drive the waterjets for the 15 knot cruise speed.

3. Approach

The reconfigurable features that were considered are:

- reconfigurable stern shape;
- transom flap;
- propulsion;
- prime movers.

It was assumed that the hull design for such a craft would be for the 40 knot operating regime, and that this would result in a non-optimum hull shape at the 15 knot cruise. If the standard configuration hull form were actually designed for a compromise between 15 and 40 knots then this would create a larger drag for the 40 knot sprint, resulting in the need for a larger gas turbine to be installed, as well as a larger Diesel engine for the 15 knot cruise.

Table 1
Principal particulars of standard vessel

	Model scale value	Full size value
Overall length (m)	5.318	98.9
Waterline length (m)	4.980	92.6
Displacement (t)	0.269	1,774

The hull form was based on an existing 5 metre long fine form model, which has a wide transom suitable for waterjet propulsion. The scale for this model to represent the OPV is $1/18.6$.

A transom flap was designed for this hull form for 40 knot operation at the OPV scale, and this was considered to be the standard vessel for the purpose of this work.

For the low speed operation an extension was fitted to negate the transom drag. A suitable extension was designed for the existing fine form, however because this has flat aft buttocks the extension was required to have a length of 14 m, which was longer than desirable to achieve zero transom immersion whilst limiting the amount of separation that occurs.

A hull form designed for this purpose could have steeper buttocks aft, with an adjustable transom flap, resulting in a shorter stern extension.

It was assumed that for the low speed the reconfigurable vessel would be propelled using a single azimuthing thruster, the waterjet inlets would be covered to reduce the drag, and some of the water in the waterjet ducts evacuated using a pump [1].

Resistance experiments were conducted using the model with and without the flap and stern extension, and at three displacements to determine the influence of increasing the displacement due to the additional mass required for the reconfiguration. The principal particulars for the model are given in Table 1.

Propulsion coefficients for the thruster and the waterjet were obtained from existing data and used to convert the effective power (measured in the Ship Tank) to the required brake power.

4. Reconfiguration concepts

In order to assess the practicality of the reconfigurable issues discussed above, two concepts were considered resulting in the following outline proposals: hinge-able; and slide-able, illustrated in Figs 1 and 2, respectively. For each of these, the stern extension would be out of the water for the high speed operation, resulting in an immersed transom and exposing the waterjet outlets.

For the hinge-able concept the stern extension would be hinged at the top edge of the transom. The stern extension could then be rotated into position as shown in Fig. 1. With this concept, the thruster unit would not itself have to be retractable, as it

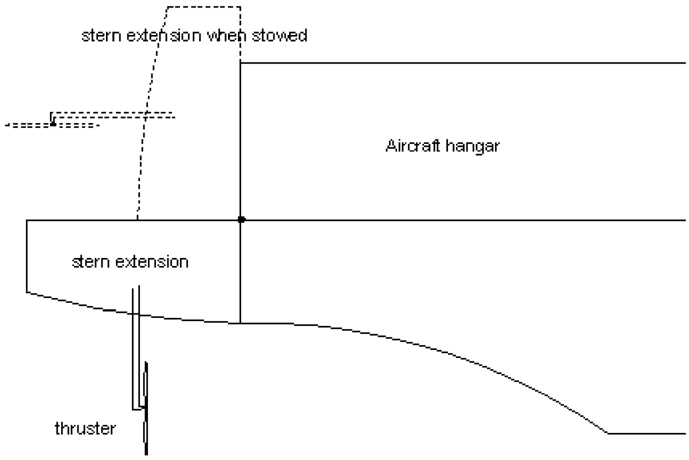

Fig. 1. Simple schematic of hinge-able stern concept.

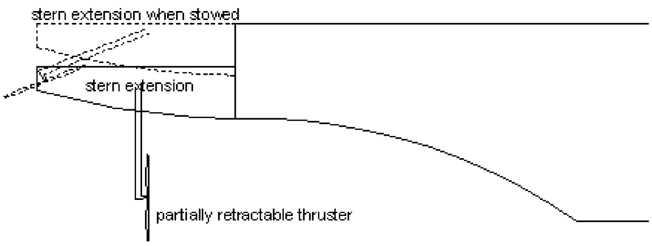

Fig. 2. Simple schematic of slide-able stern concept.

would automatically come out of the water for the high speed operation as the stern rotates. This would also make access for maintenance easier, but may cause other operational problems.

It may also be possible to make use of the additional deck space, for example, during helicopter operations, as these would not be carried out at high speed.

The second concept, the slide-able concept, would make use of a much more minimal stern extension, which could slide vertically on the transom as shown in Fig. 2. This would have a reduced mass compared to the full depth stern extension. The thruster unit could be located in the stern extension, but would need to be able to partially retract to clear the waterjet outflow at high speeds.

The transom flap would be deployed for all high speed operations, and retracted during low speed operations. This is likely to have a small cost and mass impact but was not considered in this study.

5. Mass estimates for reconfiguration

Inclusion of the stern extension and its associated machinery in a ship design would result in a mass penalty, which in turn will increase displacement and resistance. In order to quantify this penalty a study was carried out breaking the mass and cost down into their constituent parts for the various concepts outlined in Section 4.

5.1. Stern extension piece

The weight of the 14 m extension piece complete with location interfaces and locking mechanisms is estimated to be 250 tonnes. As noted in Section 3 it is likely that a shorter extension piece would be required for a purpose built reconfigurable hull form. In addition, observations during the experiments showed that at the displacement of 1,774 tonnes the full length was not required. Hence it is reasonable to assume that the realistic length of the stern necessary to give the hydrodynamic benefit would be of the order of half to three quarters of that originally assumed. This will reduce the total weight of the stern extension and associated attachment mechanisms to 200 t and 140 t for the 10.5 m and 7 m lengths respectively.

The hinge concept would need some sort of lifting mechanism which could be a rotating lifting frame hinged to the deck structure slightly forwards of the main hinge with hydraulic cylinders for actuation and it is estimated that the mass of this will be: 200 t, 190 t and 140 t for the three extension lengths.

The hinge-able extension is to be stored in the upright position for high speed operations, but this may present a significant air drag area at 40 knots, particularly with the 14 m length. The extension increases the available deck space. This could accommodate a hangar area, for example, and the required superstructure would in turn shield the stored extension. If the extension piece is to be used as a helicopter landing deck when deployed at low speeds, it would need to be designed for landing loads. This would increase the current weight estimates. With the extension stored in the vertical position and the thruster retracted, the centre of gravity position for this assembly will be some distance above the main deck level. This would move the position of the vertical centre of gravity and the negative effects of this on transverse stability would need to be evaluated. There would also be a small change in longitudinal stability which would change the trim slightly.

The slide-able concept shown in Fig. 2 would have an extension piece with a reduced depth of section relative to the previous concept, to reduce the protrusion above the main deck when stored. The thruster would need to be fully retracted to prevent drag and slamming loads at 40 knots, so the extension piece would need to have enough internal space which could be achieved by a cowling on the top surface. The means of locating, repositioning and locking the extension piece at the interface with the high speed stern would be heavier and more complex than the corresponding features in the previous concept. The mechanism for moving the extension piece would require more than a simple deck-mounted winch. This could be achieved by hydraulics, rack and pinion gear systems with slides and clamps etc. and good protection from the elements would be essential. The means of adjusting the height position would need to fit in the available space at the aft end without interfering with the waterjet system. The mass of the extension piece with adjusting and locking mechanism can be estimated as: 200 t; 180 t; and 160 t for the 14 m, 10.5 m and 7 m lengths respectively.

5.2. Retractable thruster

The propulsion requirement for low speed operation is based on a Rolls-Royce UL255 azimuthing retractable thruster with a maximum rating of 2,200 kW and a propeller diameter of 2.8 m. This gives ample margin over the estimated continuous power required of 1,400–1,500 kW, depending on the additional mass of the reconfiguration.

The catalogue dry mass of the thruster is 38 tonnes and the mass of the hull pocket to enable the thruster to be retracted is estimated to be 30 tonnes greater than the steelwork required for a smooth hull profile. The electric motor, variable speed drive and associated services and seatings are estimated to add another 30 tonnes.

Thrusters can be configured to retract, either vertically or by swinging up, into a hull pocket and the weight and cost is assumed to be the same for both types at this stage. Thrusters of this type are currently supplied to commercial standards and can only be retracted or deployed when the ship is stationary or moving at docking speeds.

As noted above, the thruster could be installed in the stern extension piece. A hull pocket would still be required in the extension piece to keep it water-tight to protect the electric systems from seawater and to reduce drag at low speeds. It may be that a non-retractable thruster is acceptable for the hinge-able concept, but this may make the thruster vulnerable to damage depending on the nature of the high speed pursuit.

The total mass of the retractable thruster will be around 100 tonnes and around 70 tonnes if non-retractable.

5.3. Waterjet covers and pump

The concept for the waterjet inlet covers is based on two openings of 6 m by 4 m which are approximately elliptical with sliding covers that are non-structural and unsealed. It would be optimistic to have fully sealable covers of this size that remained watertight throughout the life of the vessel or between dry dockings. It is more practical to have covers that fit as well as possible with a seawater leakage rate into the waterjet ducts that is manageable by pumping to reduce the weight of the entrained water.

The weight of the covers, slides and actuators is estimated to be 20 tonnes, with another 3 tonnes for a pump and pipework capable of coping with a seawater leakage rate of 10% of the duct free flooding volume per minute.

5.4. Total additional mass

A summary of the estimated additional masses associated with reconfiguration are given in Table 2.

These masses do not include any saving due to the need for a smaller Diesel engine for low speed operation, the reduction in fuel required, and the evacuation of the waterjet ducts. In addition, no attempt has been made to optimise the structure, nor to make use of lightweight or exotic materials such as aluminium or composites. As the extension piece would be expected to be in the region of 7–10.5 m for a purpose designed hull form, it is assumed that the total increase in mass due to the reconfiguration would be of the order of: 250–350 tonnes.

6. Required power

In order to determine the power required for both speeds, resistance experiments were undertaken in the 270 m Ship Tank at QinetiQ, Haslar.

The model was ballasted for each displacement to achieve level trim in the high speed configuration and the longitudinal centre of gravity (LCG) noted. This LCG was then maintained for the other configurations at that displacement. The result of this is that when in the low speed configuration the vessel was trimmed slightly by the bow, which will also have the effect of reducing the power required slightly.

The experiment was designed to investigate the effect of displacement on all the conditions tested, so each configuration was tested at each displacement. The base case is the medium displacement of 269 kg which is equivalent to 1,774 tonnes at full scale. All conditions were run over a range of Froude numbers covering full scale equivalent speeds of 10 knots to 46 knots.

The naked hull full scale effective powers extrapolated from model scale are shown, for the base displacement, in Table 3.

Table 2
Additional mass breakdown

Length of stern extension (m):	14	10.5	7
Hinge-able concept (t)	570	510	400
Slide-able concept (t)	330	300	280

Table 3
Naked hull effective powers for the base displacement (1,774 t)

Speed (knots)	Low speed configuration (kW)	High speed configuration (kW)
15	800	1,000
40	–	21,700

It was assumed that the vessel will be fitted with appendages of similar form to those on a typical warship, excluding the rudders. The drag of these appendages was estimated using QinetiQ, Haslar standard practice. This was added to the bare hull effective power given in Table 3 to obtain the appended effective power.

In order to obtain the required power delivered to the propeller (P_D) propulsive coefficients for the waterjet at 15 and 40 knots and the single thruster at 15 knots were required.

Publications such as those by Svensson [4] and Svensson et al. [3] were used to obtain the waterjet propulsive efficiency over the speed range, as shown in Fig. 3.

It was estimated, using historical data, that a representative value of propulsive efficiency for a propeller at 15 knots is 0.65.

Mechanical losses of 4% were assumed, and in addition a further 5% losses due to air intakes was assumed for the gas turbine.

The resultant required brake powers for the base case displacement (1,774 tonnes) are given in Table 4.

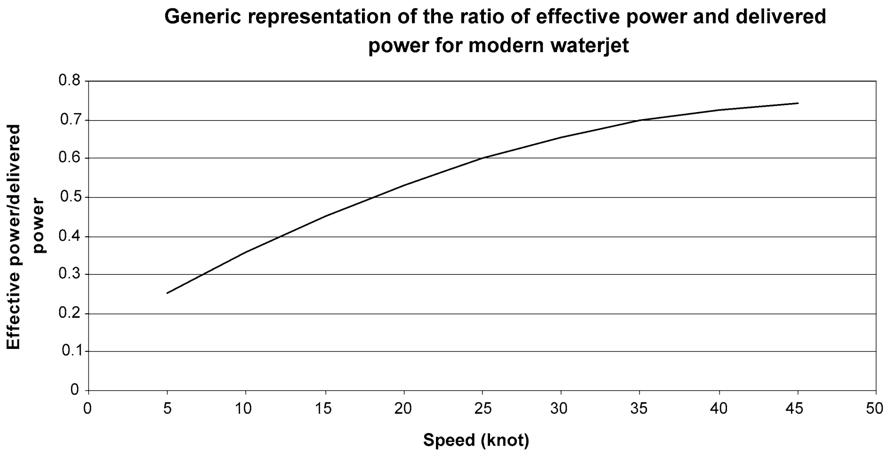

Fig. 3. Representation of ratio of effective power to delivered power taken from Svensson [4] and Svensson et al. [3].

Table 4

Required brake power for base case displacement (1,774 tonnes)

Speed (knots)	Low speed configuration (kW)	High speed configuration (kW)
15	1,400	2,600
40	–	35,000

7. Effect of displacement on required power

The model experiments were conducted at three displacements corresponding to: 1,408; 1,774 and 2,140 tonnes. The displacement of the standard vessel was assumed to be 1,774 tonnes, and the purpose of the tests at the additional displacements was to determine the effect of the mass of reconfiguration on the power required.

The naked effective power is plotted as functions of displacement for the both the low speed and high speed hull forms at 15 knots, and the high speed hull form at 40 knots in Figs 4–6 respectively.

These results are for a hull form optimised for a displacement around 1,800 tonnes and hence there is a greater than optimum transom immersion at the higher displace-

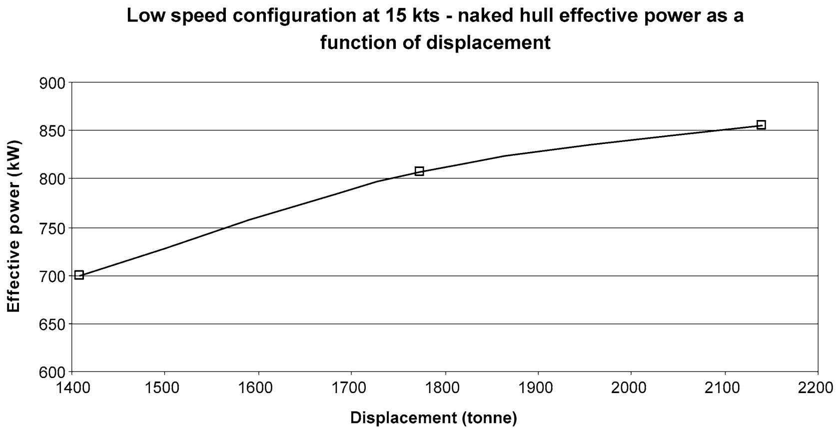

Fig. 4. Naked effective power for low speed hull form at 15 knots.

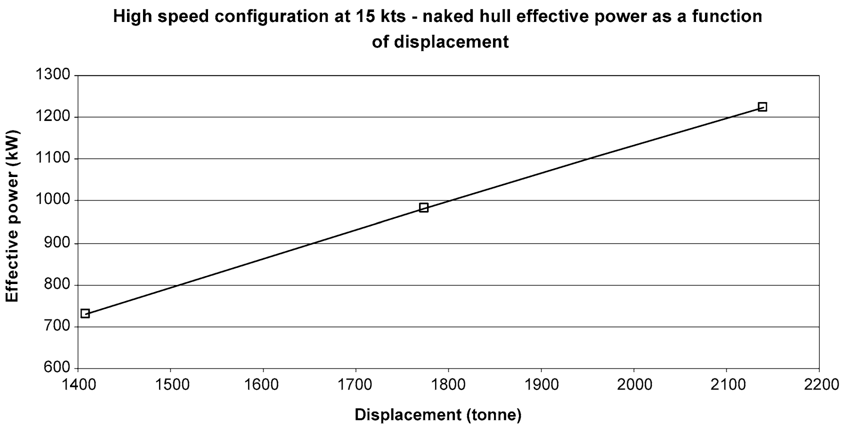

Fig. 5. Naked effective power for high speed hull form at 15 knots.

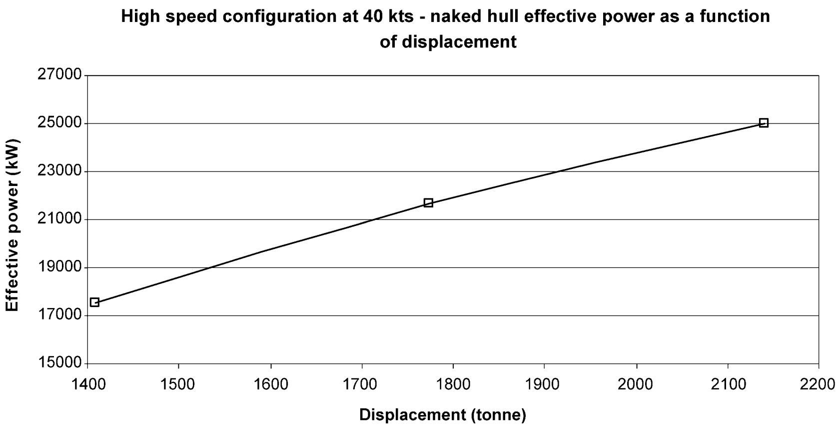

Fig. 6. Naked effective power for high speed hull form at 40 knots.

ments. The influence of running outside the design displacement in the low speed configuration is considered to be negligible as this configuration has no transom immersion. This is not the case in the high speed configuration and so a significant impact on resistance would be expected as the displacement is increased.

If a hull were designed for a higher displacement, as would be required for the reconfigurable vessel, it would therefore have a transom immersion optimised for that displacement. The effect of this would be to reduce the power required for the increased displacement at 40 knots.

Series 64 data [6] which covers a range of displacements with constant transom area ratio, was used to estimate the effect of increasing displacement whilst maintaining optimum transom area ratio. This allows a better representation of the influence of increased design displacement, as would be required for the reconfigurable vessel.

The results from the experiments with the non-optimised transom area gives an increase in brake power required at 40 knots as a function of increase in displacement ($\mathrm{d}P_\mathrm{B}/\mathrm{d}\Delta$) of approximately 16 kW per tonne, whereas the estimated value from the Series 64 results with the constant, optimised, transom area is 9 kW per tonne. For the purpose of this study the latter value has been used, as it is assumed that this is what would be achievable with a well designed hull form.

8. Potential annual fuel saving

The annual fuel saving will depend on a range of factors including: actual additional mass required for the reconfiguration; percentage of time spent at each of the two different speeds; total annual deployment; specific fuel consumption of the prime movers; and fuel cost.

By averaging data available for widely used drives it has been determined that a specific fuel consumption of 190 g/KWh for a Diesel at 15 knots (Wartsila web site) and 225 g/KWh for a gas turbine at 40 knots (Rolls-Royce web site) would be representative for this study.

A fuel cost of £380 per tonne was assumed.

The annual fuel savings for the reconfigurable vessel, compared to the standard vessel, are presented as functions of reconfiguration mass for a range of operating profiles in Figs 7 and 8.

From the preliminary mass estimates conducted in Section 5, it would seem reasonable to assume that for a well designed concept the additional mass required would be of the order of 250–350 tonnes.

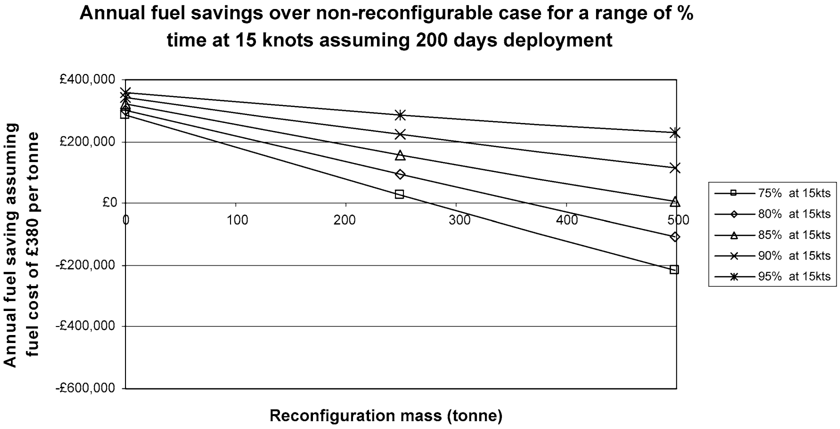

Fig. 7. Annual fuel saving for an annual deployment of 200 days (24 hours) with a $dP_B/d\Delta$ value of 9 kW per tonne.

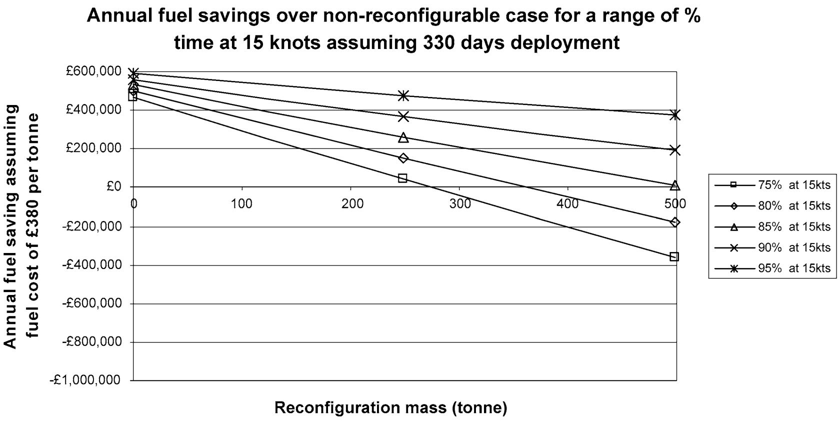

Fig. 8. Annual fuel saving for an annual deployment of 330 days (24 hours) with a $dP_B/d\Delta$ value of 9 kW per tonne.

As can be seen from Fig. 8, this means that if an OPV of this size spends 85% of its time at 15 knots it would have an expected annual fuel saving in the range of £175k–275k, assuming a fuel cost of £380 per tonne.

9. Application to other vessel types

The primary alterations due to reconfiguration are a reduced transom immersion and a more efficient low speed propulsion unit. There is no reason why these basic principles cannot be applied to vessels of different type or size.

The primary penalty associated with reconfiguration is the extra mass of the stern extension which must be carried whilst at high speed as well as low speed. If this can be kept to a minimum then the saving should be seen across a range of vessel sizes. For larger vessels it is likely that the mass of the stern extension will be a smaller proportion of the total displacement than for smaller vessels, however the mechanical arrangements to enable reconfiguration may be more difficult.

As the purpose of the stern extension is to remove the transom drag at the low speeds, its size and effectiveness will depend on the magnitude of the optimum transom immersion for the high speed. It is likely that the sprint speed for larger vessels will be at a lower Froude number, hence the optimum transom immersion will be less, resulting in a lower transom drag at the low speed regime. This will reduce the hydrodynamic advantage, however it will also reduce the mass of the stern extension, and therefore the penalty associated with this.

The generic operating profile of the OPV is particularly conducive to optimisation for two speeds as the operations are concentrated at these two speeds. Equally, a motor yacht, required to transit between cruising grounds at low speed, but with the ability to sprint at high speeds, could benefit from the reconfigurable concept. In this case it may actually be more appropriate to leave the stern extension piece, with associated thruster, ashore during the time spent at a particular cruising grounds, and only fit this for the transit phase. The stern extension piece could also contain the Diesel engine for low speed operation, and fuel tanks.

For a vessel with less concentrated operational speeds, or a lower difference in speed between cruise and sprint, then the advantages of reconfiguration would reduce. Also, if the sprint speed was below about 30 knots, waterjets would not be used, and the difference in propulsive efficiency for the high speed and low speed propulsion methods would be less.

It may also be feasible to retrofit a self contained stern extension to a ship designed for high speed, which due to changes in operational profile spends more time at low speed. This could contain all the propulsion and other equipment required for the low speed configuration.

The current size of vessel and cruise speed requires a propulsive power for the low speed which is compatible with existing commercially available retractable thrusters. If the vessel size, and/or cruise speed were such that the power required was greater than available thrusters, this could have an impact on the cost.

10. Concluding comments

In order to investigate the benefits of a reconfigurable hull form, this concept was applied to a 93 m OPV with an assumed operating profile of 15 knots for 85% of the time and 40 knots for the remainder of the time over an annual deployment of 330 days.

This resulted in an annual fuel saving of the order of £175k–275k at a cost of £380 per tonne. This is sensitive to the additional mass of the reconfiguration concept, as this causes an increased power requirement at 40 knots.

It was noted that this concept could be applied to vessels of other sizes and operating profiles, including motor yachts.

Notation

LCG	Longitudinal centre of gravity
LWL	Waterline length
OPV	Offshore Patrol Vessel
P_B	Brake power
P_D	Delivered power
Δ	Displacement
ρ	Water density

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