Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title: Deliverable 4.8: Recommendations to improve current operational practice

Contents

Publishable Executive Summary

The aim of this task is to provide recommendations to improve current operational practice; specifically for ships equipped with Azimuthing Control Devices (ACD's). The aim is also to provide feedback from the Task Analysis exercise to those responsible for the manoeuvring design and performance analysis specialists active in Hydrodynamic Modelling. The objectives are to improve the safety and security of ships through enhanced understanding and design.

In summary, we recommend the following;

- We recommend developing good operational procedures, using universal terminology and mandatory ACD training.
- We recommend that all bridge controls, by design, should be standardised and incorporate synchronised control systems as a safety feature.
- It is recognised that any 'hands on' approach does have a tendency for a single point error, that may not be picked up by other members of a 'bridge team' and we would recommend this is an area of further research.
- We recommend that further work is required to develop 'result orientated' commands (if verbal commands are used at all).
- Recommend further research to determine the best method of executing an 'Emergency Stop'.
- Recommend performing finite element analysis using global-local techniques to ascertain structural loadings.

1 Introduction

The aim of this task is to provide recommendations to improve current operational practice; specifically for ships equipped with Azimuthing Control Devices (ACD's). The aim is also to provide feedback from the Task Analysis exercise to those responsible for the manoeuvring design and performance analysis specialists active in Hydrodynamic Modelling. The objectives are to improve the safety and security of ships through enhanced understanding and design. This report should be read in conjunction with Task 3.9: '*Integrating knowledge by recommending training programs'* which looks at training.

2 Recommendations for safe operation

A clear majority of pilots and ship masters have expressed an opinion that there is the need for specific training courses for ships equipped with Azimuthing Control Devices (ACD's), in particular to enhance knowledge and skill in handling ships in a safe and intuitive manner with Azimuthing propulsion devices in varying critical situations. This is necessary in order to improve safety at sea, especially when berthing or unberthing.

However, whilst Ship Handlers (Masters and Pilots) overwhelmingly want to be trained to use ACD's (who pays?) and that STCW requires them to be trained, depending on one's interpretation of the Code, many Ship's Officers, Masters and Pilots who operate ACD's have not received training in the use of ACD's! Is there something wrong with current regulation, as there appears to be a miss match between what is expected and what in happening in reality?

There are some recommendations to improve safe operational practice:

- Standardisation of ACD design and terminology (either across a fleet or better still across the whole industry)
- Synchronisation of ACD's in the different manoeuvring positions which simplifies procedures for changing control
- Design of Haptic feed-back systems informing the user of the status of the system
- Develop and practise on board procedures
- Be practised in using equipment when a unit fails
- Be familiar with emergency scenarios and procedures
- Promulgate manufacturers recommendations/limitations of equipment
- Mandatory training in ACD ship handling for watch keeping officers, masters and pilots

Sections 2.2 and 2.3 in Deliverable 4.9 highlight how manoeuvring errors may occur as a result of different terminology and different design features used by individual ship owners/operators. While there may be an argument from equipment manufacturers that standardisation stifles innovation and development, this argument is not upheld when examining the design and layout of aircraft cockpits and instrumentation, where standardisation is very much the norm and yet development and improvements still occur.

Task 4.4 carried out a review of accident and incident reports to establish the type and commonality of various accidents and incidents. It concluded that manoeuvring error and transfer of control issues are relevant in 60% of the incidents. With regard to transfer of control issues accidents attributable to this action could be reduced or eliminated if the bridge wing and central bridge console controls are synchronised so that they follow each other. In this way mistakes can be avoided as control can be transferred by just one single movement, that of a switch being activated, rather than a series of actions that could easily be mishandled.

Work has been carried out and is ongoing into the use of Haptic controls that produce an output which is felt by the user rather than seen or heard. Such controls would be beneficial to the user to alert him/her when they attempt a manoeuvre that will be alerted by the operational mode the controls are currently engaged in or when the user attempts a manoeuvre that may be detrimental to the operational efficiency of the propulsion unit.

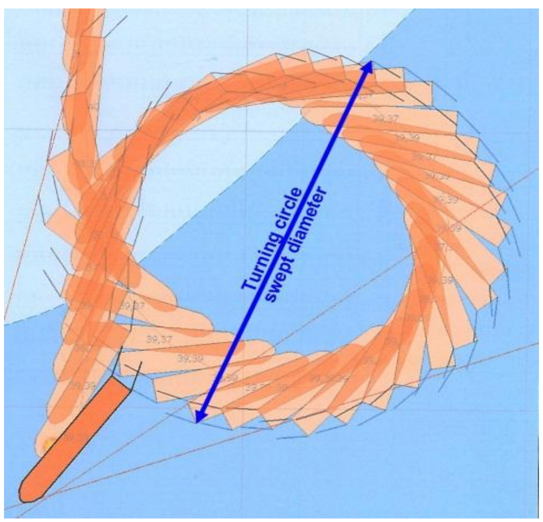
PRL carried out trials with their podded scale manned model in emergency stops and the following table is reproduced to show the results obtained;

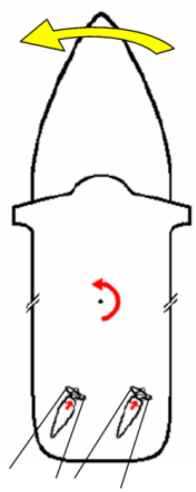
Synchronisation of controls

POD CRASH STOPS - Tracks on the PORT REVEL Lake

Track	Date	Start	Start	Pod settings		Wind		Starboard turning	Stopping	Observations
N°		time	speed	port	stb	speed	direction	diameter	distance	
	yyyymmdd	hh:mm	kn	rpm/azim	rpm/azim	kn	deg.	ship lengths	ship lengths	
2.0	20100503	09:46	10.0	0/0	0/0			-	4.1	Propellers in line and stopped (induces 3 L lateral transfer !)
2.1	20100503	10:46	13.5	-100/-100	0/0			-	3.0	Reverse propeller to full negative rpm (= full astern)
2.2	20100503	10:56	13.5	100/100	-180/180			-	2.3	Turn both pods 180° outboard with full positive rpm
2.3	20100503	11:06	14.0	100/100	180/-180			-	2.1	Idem inboard turning (Pod way stop)
2.4	20100503	11:15	13.5	100/100	90/-90			-	2.9	Turn both pods 90° inboard with full positive rpm (transverse arrest)
2.5.1	20100503	09:30	9.5	0/0	90/-90			-	5.0	Idem with propellers ordered at stop (induces 2.5 L lateral transfer !)
2.5.2	20100503	09:37	9.5	0/0	-90/90			-	5.0	Idem with pods turned outboard (induces 2.5 L lateral transfer !)
2.6	20100503	11:26	13.5	-100/-100	-60/60			-	2.6	Turn both pods 60° outboard with propeller ordered at full negative rpm
2.7	20100503	11:34	13.5	sequence				-	4.9	Turn both pods 35° outboard with reduced rpm until speed reduced to 8 kn …
								-		then turn both pods further to 180° with increased rpm

2.8	20100503	11:44	13.5	sequence				-	4.4	Reduce to 80 rpm, then turn 180° outboard, then 11kn/50rpm, 8kn/30rpm
2.9.2	20100503	11:54	13.5	sequence				-	6.1	Deceleration: 80rpm, then 11kn/50rpm, 8kn/30rpm & turn 180° outboard
2.10	20100503	12:03	13.5	100/100	-45/-135			-	2.0	Turn port pod 45° outboard and the stb 135° inboard with full positive rpm
										(induces 1.5 to 2 L lateral transfer)
12	20110721	10:07	13.0	100/90°	100/-90°	5-10	200	-	2.9	Transverse arrest (= Azipilot test 2.4 gives 2.9 SL also)
13	20110721	10:32	13.5	100/seq	100/seq	5-10	150	-	2.4	Idem, then 180° at 3 kn
14	20110721	10:38	13.5	100/seq	100/seq	5-10	150	-	2.4	Idem, then 180° at 3 kn





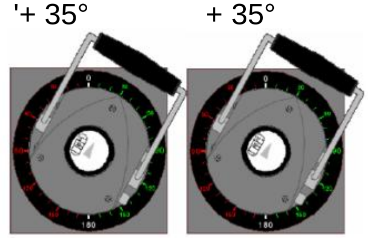
'Definitions:

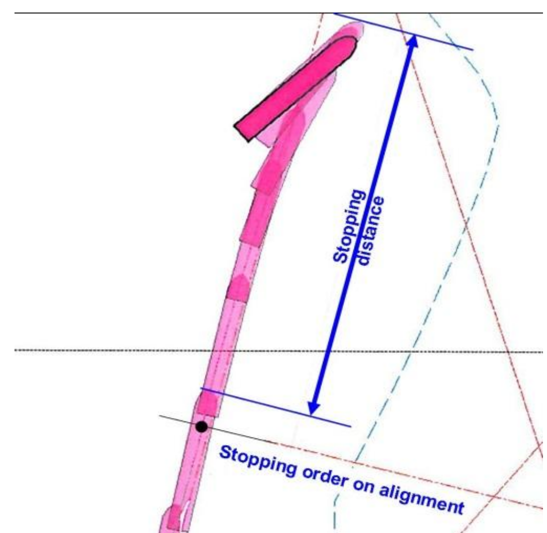
'+ rpm: positive rpm ("ahead")

'+ 35°: turn pod 35° clockwise

' + rpm   + rpm

'+ 35°   + 35°





Column “Pod settings” gives rpm & azimuth for each pod. See sign definition on sketch above
Column “Stopping distance” is given in ship lengths.

Complete tracks are given in the report, but let’s just look at the figures for stopping distances (with initial speed of 13-14 kt):

- just stop the engine: stop after 4.1 SL (test 2.0 with initial speed of only 10 kt)
- reverse to full negative (full astern): stop after 3.0 SL (test 2.1)
- turn pods 180° OUTBOARD: stop after 2.3 SL (test 2.2: not the best, but close to next one)
- turn pods 180° INBOARD (Pod Way stop): stop after 2.1 SL (test 2.3: the shortest distance we measured)
- turn pods 90° INBOARD (transverse arrest): stop after 2.9 SL (test 2.4 & test 12)
- turn pods 60° OUTBOARD with rpm full astern: stop after 2.6 SL (test 2.6: not so bad)
- turn pods 90° INBOARD, and then further to 180° when speed is reduced to 3 kt: stop after 2.4 SL (test 13 & 14: quite good also)

Current definition as defined by ABB Documents;
Turning INBOARD – pulling pod - turn the propeller end INBOARD
Turning OUTBOARD – pulling pod - turn the propeller end OUTBOARD

The evidence from these trials does conflict with manufactures recommendations – to turn the pods OUTWARDS in a ‘Pod Way’ stop as being the shortest distance to stop the ship, as the trials found that turning the pods INWARDS produced the least distance (2.1 SL as opposed to 2.3 SL). Whilst the difference is not large, further research is recommended, especially to determine the likely damage to the pod structure should this manoeuvre be conducted from Full Speed.

3 Recommendations for safe operational procedure

In Task 4.2 some Shipping Companies impose restriction on their Masters with regards to the use of ACD’s, often in response to the Manufacturer’s recommendations, in order to prevent excessive wear, damage or failure, in particular to the bearings (which were the recognised weak part of the unit in the early part of the development of pods).

This imposes numerous restrictions upon the Master in operating ACD’s and as a consequence the strategy for any manoeuvre has to take these restrictions into account at and early stage of planning each manoeuvre.

Generally, recommendations made by the manufacturer are as follows:

- Operate pods as gently as possible
- Avoid reverse power (reverse rpm)
- Maintain positive rpm
- Crash stop to be avoided

- Avoid wash onto another pod(s)
- Avoid applying large angles of rotation
- Maintain minimum revolutions
- Avoid large differences between rpm and ship speed
- Avoid unpowered rotation at low speed
- Avoid powered rotation below 25 rpm and preferably 30 rpm
- Avoid cycling between zero 25 to 39 rpm
- Avoid cycling between forward and reverse rpm
- Avoid wash over unpowered pod
- Avoid flow from a pod directly entering the propeller of the other pod

Compared to conventional shiphandling, ACD's are completely different to what a trained and experienced shiphandler might expect. The restrictions listed above, when adhered to, add another level of complexity as well. Hence, the importance of developed operational procedures, combined with specialist training, to ensure that ACD's are operated efficiently and safely. In this project, we have met trained shiphandlers who operate to set procedures and have gone on and gained vast experience, who are a joy to watch. On the other hand, we have met untrained shiphandlers who are a great cause for concern and many others, somewhere in between, desperately struggling to control their vessels.

Without good operational procedures, mistakes can easily be made which can be very costly and unsafe. Whist some companies have developed excellent procedures, these can vary from company to company and for pilots this is of great concern as there is not a 'uniform industry' method. This can vary from the pilot being excluded from conning the vessel, to terminology that can be, at best confusing. On vessels where no operational procedures exist the command structure is severely compromised.

Whilst shiphandling, when things start to go wrong, due to large gust of wind or an equipment failure, things tend to go wrong extremely quickly, hence the need for good operational procedures and appropriate training, as the foundations on which experience is then gained.

Task 4.3 highlighted that a number of past accidents have occurred when changing control from a central bridge console to a bridge wing console. We have noted that apart from good operational procedures, where the design has synchronised controls, this simplifies the procedure and there is much less chance of error. We therefore recommend that all bridge controls, by design, should incorporate synchronised control systems as a safety feature.

Regarding the way the manoeuvring orders are given, the suggestion of a standardized set of sentences in Task 4.4 (Baken and Burkley "Azipod Manoeuvring Terminology" (March 2008)) could represent the starting point of a wider and better shared system of instruction exchange, which could help all people involved in manoeuvring to be informed about, without risks of misunderstandings due to the wording used. Having said that, generally the control of ACD's tends to be a tactile 'hands on' practice and giving verbal commands in a multi unit system would be prone to errors in the translation and a rather rigid method of using this type of versatile propulsion equipment. We would contend that ACD's are a departure from conventional propulsion systems, which historically have been operated by verbal commands. Current practise with Controllable Pitch Propellers (CPP) and bow thrusters, especially with twin screw configurations, already lends itself to a 'hands on' approach and a departure from historical verbal commands. ACD's simply take this another step further and do not need any historical baggage of 'verbal commands'. However, it is recognised that any 'hands on' approach does have a tendency for a single point error, that may not be picked up by other members of a 'bridge team' and we would recommend this an area of further research. A pilot of an aircraft has always operated with a 'hands on' approach and has never used verbal commands but is supported by strong procedures and often a co-pilot.

We have also noted that the above terminology when applied to Azipods (pulling pods), if also applied to pushing pods, then the result is quite different. Pilots in particular can be confused by this, if they fail to comprehend (or it is not explained) whether a pod is pulling or pushing.

We therefore recommend that further work is required and suggest that 'result orientated' commands (if verbal commands are used at all) may well be a better approach.

Another area that we have discovered that causes confusion are the terms 'OUTWARD' and 'INWARD, and suggest that further research be conducted to establish a method of terminology that is not open to differing interpretation.

When using multiple pulling ACD's, it is better to tactically operate the device using a 'positive thrust'. This is generally a better strategy to meet the manufacturer's limitations, as well as, recognising the loss of power efficiency resulting from reversing the pitch could be as much as 60%. This can be caused by the flow of water entering the propeller being disturbed by the pod body, as well as, by the propeller design. So, it is preferable to maintain 'positive thrust' and turn the pod, changing its direction, instead of reversing the pitch.

This strategy also helps when, avoiding cycling between zero and 25 rpm and trying to maintain a 25 rpm speed at all times and avoiding a large difference between rpm and ship speed. Avoiding direct wash from one unit directly into the another and avoiding water flow from one unit entering the propeller of the other unit, can also be best achieved by a strategy of directing 'positive thrust' water flow away from the hull. Thus a neutral effect can be achieved by using 'positive thrust' from two pods being directed away from the hull, in opposite directions, which forms the starting point of varying power and direction (vectoring) to achieve shiphandling aims, as opposed to the simplistic 'T-bone' method (one unit fore and aft, the other operated transversely) thereby complying with the manufacturers limitations.

4 Recommendations for design for safe operation

4.1 Introduction

The aim of this task is to provide recommendations to improve current operational practice; specifically for ships equipped with azimuthing control devices. The aim is also to provide feedback from the Task Analysis exercise to those responsible for the manoeuvring design and performance analysis specialists active in Hydrodynamic Modelling. The objective is to improve the safety and security of ships through enhanced understanding and design by providing recommendations for design for safe operation.

4.2 Background

With the introduction of any new concept comes, to some extent, a venture into the unknown. Even seemingly simple innovations can sometimes play host to some remarkable surprises; possibly considered obvious in hindsight, these are often virtually impossible to predict. This type of uncertainty is well understood by philosophers of engineering design and must be managed in a way that will limit the risks. In general, only a limited amount of innovation is introduced into any new design, reducing the impact of any one feature not turning out as planned. However, in some cases the market demand for a particular product outstrips the risks posed by extensive innovation. That is to say, there is sufficient potential profit available to offset the losses associated with any unexpected failures. The development of the azimuthing pod drive falls very much into the category of this type of ‘market driven action’. The potential benefits have proved very attractive to ship operators who, in turn, have demanded more and better from the pod manufactures. This forced evolution has placed significant demand on the pod manufactures to respond, authorities to legislate and on the crews of pod- driven ships to learn how to best operate these new technologies. The aim of this section of the report is to provide the practicing naval architect with a background to the technology and general guidance for its application.

4.3 Considering the design process

The purpose of the following section, and the main objective of this report, is to make general discussion of the engineering implications when selecting ACD’s, and more specifically, azimuthing pod-drives. One key aspect of design is commonly known as the design spiral. In this concept it is acknowledged that any ship design, or any engineered object for that matter, is an iterative process. The so named ‘spiral’, alludes to the process of passing ever closer to the final solution. However, to achieve this it is first important to identify the subject disciplines that should lie around the spiral. Of course, as a design progresses, we need to consider a great many disciplines, however, at the preliminary design stage, it is important to identify only the most critical or most influential items. In this way, the true preliminary design can be conducted, as an iterative process, ensuring the relative feasibility of the outcome design. For this purposed, the key disciplines are herein presented in a design-spiral form.

The key disciplines applicable to the design-spiral for a pod-driven ship are addressed; outlined in Fig. 1. In the given figure, the process and be considered to begin with the identification of the main dimensions including the definition of the hull-lines. Notably, the motion dynamics, and specifically the manoeuvring performance, come necessarily very early in the list. Manoeuvring is of course a somewhat obvious subject to have early on the list for a ship being design, predominantly, for its manoeuvring performance. It is important however to note that this must necessary be preceded by a clear definition of the hull-lines as the manoeuvring calculations are very sensitive to these.

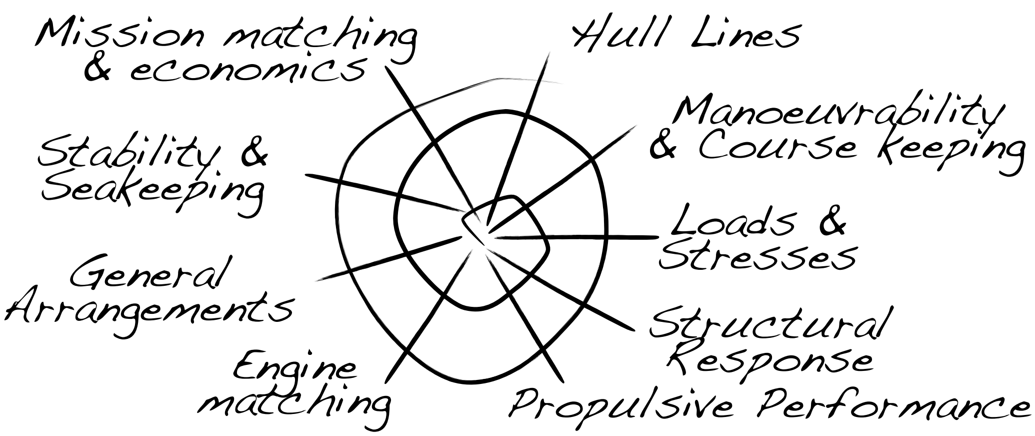


Fig. 1 – Suggested design-spiral

After the initial manoeuvring induced loads and stresses are calculated the structural response can be evaluated and an approximate figure for the steel-mass proposed. Given also the hull-lines, the propulsive performance can be estimated and the engine selected. Next, given the above, it is possible to take a first stable at the general arrangement, and thus obtain an initial estimate of the centre of mass and its relative radii of gyration. Stability and seakeeping characteristics can then be evaluated. Finally, with the above information at hand, the design can be evaluated by comparing it to the necessary desired mission profile and its cost effectiveness can be considered.

Taking these main points into consideration, the following sections make comment on each of the above items. Also, some issues related to specific types of design are touched upon including, both ice applications and fast ships.

5 Hull-lines

In practice, the use of any ACD requires a significant modification to the stern-region of the ships hull. To make room for the azimuthing capabilities, the hull must become more 'prammed' and consequently broader at the stern; to maintain buoyancy. The aft-body water-plane area increases; moving the position of the longitudinal centre of flotation (LCF) toward the stern of the ship. Also, a reduction in the aft-body volume is often unavoidable and, for constant displacement, the resulting increase in forward-body volume moves the longitudinal centre of buoyancy (LCB) forward. Accompanying the hydrodynamic influences of such a modification, the change in LCB necessitates a change in the longitudinal centre-of-mass, which further influencing the dynamic behaviour of the ship.

The central ‘skeg’ or ‘deadwood’, including any stern bulb, characteristic of a hull-form designed for a conventional propulsion arrangement, has a significant influence on the dynamic behaviour of the ship. This fin-like structure, situated deep and well to the stern of the ship, serves to increase the course-stability as well as influencing the roll damping; see Fig. 2 (left). On the other hand, the more ‘prammed’ stern-form, characteristic of a hull-form designed for pods, has no tail fin so to speak of; see Fig. 2 (right).

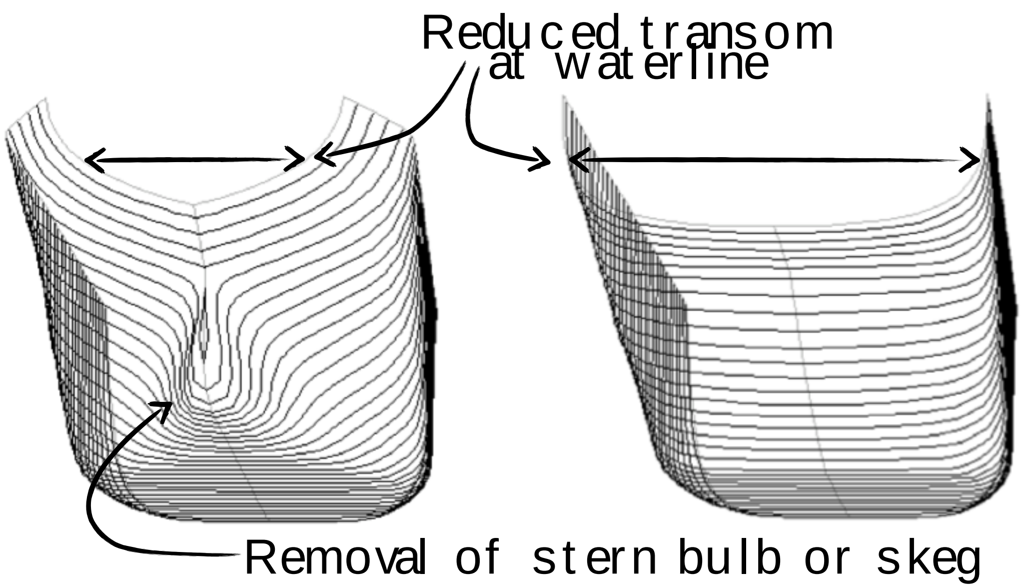


Fig. 2 – Modification on stern for ACD’s

6 Manoeuvrability and Course-keeping

The manoeuvring performance is probably the most important area to consider when designing a ship with ACD’s. After all, the primary motivation for selecting ACD’s would most likely be the enhanced manoeuvring performance. It should however be remembered that manoeuvring performance can not be optimised in the conventional sense; as the best design is based more on a qualitative assessment than a quantitative optimal minima. Ships spending a greater proportion of their time at sea may be more suited to a high level of course-stability, whereas ships predominantly manoeuvring in close-quarters may be better suited to lower or even negative course-stability. While ACD’s can offer good solutions for either of the described missions, the most distinctive advantage is the ability to provide a control force with low or even zero ship speed. A rudder can only exert a control force when it is moving through the water whereas a pod enables the propeller thrust to be used for control; even form a dead-stop. Not only does this remove the need for stern thrusters and in many cases tug assistance, but also it significantly improves the action and safety of a ships operation in confined waters. To incorporate the advantages without introducing any detrimental tendencies it is important, at the preliminary design stage, to ensure that the proposed design is at least feasible with regard to the manoeuvring performance.

Although the IMO manoeuvring criteria are not specifically intended as design rules they do serve to ensure that the designs are feasible. Notwithstanding, the direct application of the existing manoeuvring criteria to ACD ships is not specifically stated. The question of equivalence when applying the criteria with like-for-like helm-angles has been investigated, for pod-driven ships; Woodward (2005). The study reaches the definitive conclusion that, the IMO manoeuvring criteria 'Resolution MSC. 137(76)' provide equivalent information about the manoeuvring response of pod-driven ships as for conventionally propelled ships; and can thus be applied directly. The study also points out that hull-forms suited to the application of pods can have poor course-stability characteristics. And failure to address this at the preliminary design stage can result in a ship that cannot meet the yaw-checking criteria. Noting that, this is primarily a design issue and the existing IMO criteria provide an adequate benchmark to impede the development of poor designs.

The effects of the changes in hull-form have significant impact on the manoeuvring behaviour. Similar pram stern forms have been experimented with in the past for various reasons; including some promising resistance characteristics. However, failure to consider the effects on course-stability at the design stage has resulted in some unpleasant surprises. If other characteristics of the ship tend toward a less than stable form then, pramming the stern can result in a ship with such severe tendencies that it is impossible to control; neither by man nor machine. In some cases, the retrofitting of large rudder like fins on the aft quarters has been required to rescue the design. Neglecting the effect on manoeuvring behaviour caused by changes in the stern-form can have serious and costly repercussions.

To insure that the preliminary design will satisfy the IMO manoeuvring criteria, and is thus feasible, a reasonable estimation can be obtained using derivative prediction equations, Woodward (2005). In the first instant, semi-empirically derived derivative estimates can be used, through a first principles approach to ensure that the proposed design is neither too stable nor too unstable. Then, as the design progresses, the estimated derivatives can be used in combination with numerical simulation to better understand the characteristic manoeuvres. As the design progress further still, the derivative estimated should be updated with captive-model test results to offer better estimations of the characteristic manoeuvres. Moreover, if the design is significantly different from any which have gone before, the numerical simulations should be calibrated by comparison with free-running model tests. This can help to identify any unusual phenomena, specific to the design, but not accounted for in the numerical model used for the simulations.

In general for ships with ACD's, it is appropriate to push the design to the more course-stable end of the feasible region. After all, an ACD can offer a significant control force to steer a stable ship however, there are significant detrimental effects related to poor course-stability. It is worth noting that increasing the size of the strut or adding a fin below the nacelle, will help to increase the inherent course-stability of the ship. However, this increase in control surface area will also increase the control force generated by the pod; which can end up being greater that desirable from a structural design point of view [see also the next section on Loads and Stresses]. Thus, the best approach can be to try and make the hull-form course-stable in the first instant.

7 Loads and Stresses

While the large control forces generated by pods are good from a manoeuvring point of view, their accurate prediction becomes all the more important for estimating the induced loads and stresses. Commonly use slew rate criteria have their origins as a measure of the steering gear capacity; thus rendering them inappropriate for limiting dynamic loading effects. Further, while the steady state loading is relatively easy to both predict and measure, using scale model tests, the dynamic effect prove more difficult. Clearly, the acceleration related forces induced when slewing a 50 tonne rudder are quite different from those for a 500 tonne pod.

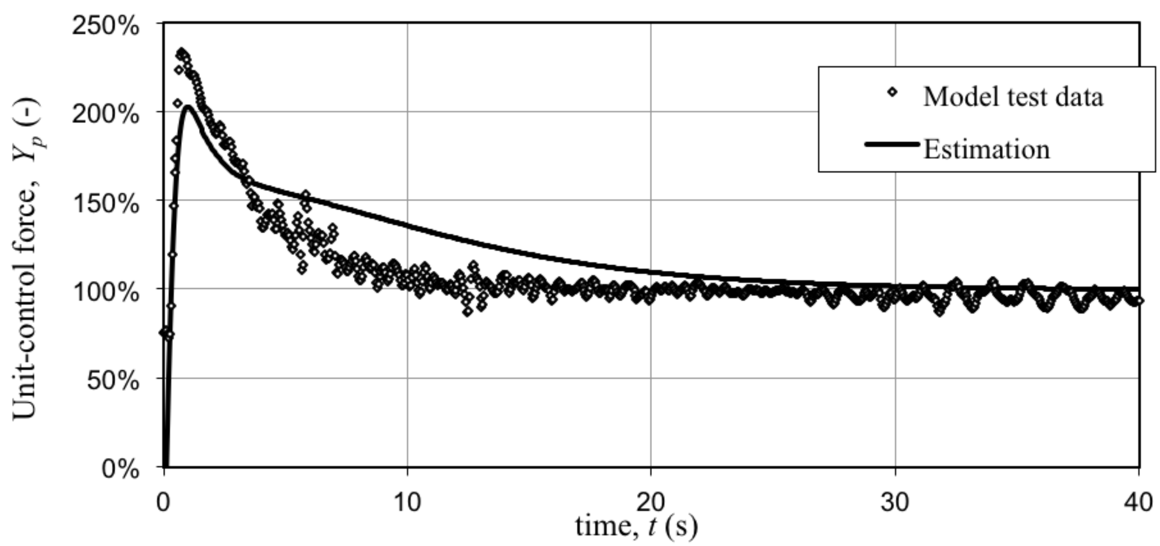


Fig. 3 – Example of dynamic loads on pods

When using predictions for only the steady state condition it is possible to seriously underestimate the total forces acting on the pod, Woodward (2005b). Figure 3 shows both an estimation and measurement of the side force generated by a pod when inducing a 35 degrees helm turning manoeuvre.

The plot is normalised by dividing by the mean steady state value when the ship is in a steady turn. Cleary, the dynamic response at the start of the manoeuvre can be more than double the loading. The numerical simulation algorithm includes additional terms to account for the mass-inertia and added-mass of both the propeller and pod-body; presenting a good indication of the origins of these dynamic 'spike' load. The time-domain response of the propeller shaft can also make some contribution. Even for the constant-torque model, characteristic of an electric motor, the rpm can be initially sustained by the shaft mass-inertia; thus presenting a thrust greater than that expected in the steady state condition.

This apparent acceleration dependency again indicates the importance of course-stability of the ship. A less stable ship will accelerate into a turn more rapidly and thus suffer greater dynamic loads.

Somewhat counter-intuitively, increasing the pod lateral area can be the best solution for limiting peak loads. While this will increase the force generated in the steady state it will also increase the course-stability thus reducing the acceleration and associated dynamic effects.

Generally speaking, the loads induced by the pod can be divided into three contributing components: those generated by the propeller; those generated by the pod-body; those generated by gyroscopic precession [see Fig. 4 for the following reference coordinates]. For the propeller, clearly there is a thrust load (acting in x11), but there is also a side force apparent when the propeller is placed at an angle of attack to the flow (acting in x22). While this side force is generally small compared to the thrust, its lever about the slewing axis can be used to balance other loads (acting in x66). For the pod-body, there is both a lift force (acting in x22) and a drag force (acting in x11). While, the drag force is comparatively small compared to the thrust, the lift force is typically 3.5 times larger than the thrust. Also, this lift force can present a large moment about the slewing axis (x66); warranting careful attention regarding the position of the centre of pressure in lift and the slewing stock axis.

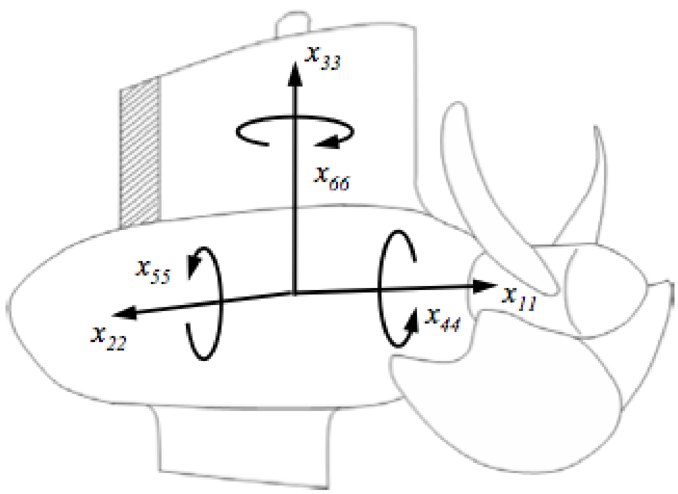


Fig. 4 – Pod-fixed coordinate system

The gyroscopic precession can be easily missed, as manoeuvring tests tend not to measure loads in the vertical plan. In brief, if a mass which is spinning with its rotational axis in the horizontal plane is forced to move on a curved path within that horizontal plane then, it experiences a moment about the axis of rotation in the vertical plane. More objectively, a pod that is forced to slew both by helm control and/or ship yawing motion, and with the motor spinning inside it, will experience a pitching moment (acting in x55). This pitching moment can be significant in magnitude (a ball park figure would be twice the propeller shaft torque) and acting about the length of the propeller shaft, as it does, must be absorbed by the shaft bearings.

8 Structural response

Within the FASTPOD project many detailed studies were conducted regarding the pod loading. It is reported that the pod foundations generally fulfills local strength criteria (permissible V. Mises stress 175 MPa for Norman steel), providing that the scantlings meet rule requirements; Konieczny (2005). However, it is also pointed out that the fatigue endurance requires a more in-depth analysis for critical areas and the assessment of fatigue endurance is strongly dependant on the accuracy of the stress range calculations. Standard approaches based on stress concentration factors can lead to excessive error in results due to complicated loading patterns and 3D effects. Also, because there is no general valid definition (except for very simple cases), evaluation of normal stresses based on approximate analysis can be another source of error. To avoid these inaccuracies, the conclusion of the work recommends performing finite element analysis using global-local techniques. Thus, after a course mesh global analysis of the entire ship is performed, a fine mesh local analysis of the structural details should be performed using the former study as input for the boundary conditions.

9 Propulsive performance

While it is difficult to generalise for all ACD’s, the use of pods over conventional propulsion arrangements can offer a 6~7% increase in the propulsive efficiency depending upon the pod geometry and other factors. Much of this may be achieved by the reduction in appendage drag due to the removal of the conventional propeller shafting and shaft brackets. A proportion may also be attributed to the improved wave making performance due to favourable interaction between pod and the stern section of the hull as well as the reduced surface area, thus frictional drag, offered by the prammed stern-form. The pod propeller can have higher efficiency than its counterpart propeller in isolation due to flow deceleration for some pod configurations – and propeller race rotational energy gains for other pod configurations. The efficiency gain can be as high as 10% but some of this is lost to the resistance of the pod-body due to it own frictional- and form-drag.

More specifically related to the propulsive performance, puller-type pods can benefit from a more uniform inflow allowing the propeller to be loaded more closely to the cavitation limit. The more common twin puller-type pod arrangement can benefit from a very uniform wake field. In addition to the relatively undisturbed flow, the pod propeller shaft can be inclined to place the propeller plane at right angles to the flow; where the flow has some upward movement due to the upsweep of the stern-form. Clearly, as the wake field is less influenced by the ships hull, less advantage can be gained from flow deceleration. However, while the quantitative advantages must be balanced the qualitative advantages favour the pod solution. Not only can the uniform inflow reduce cavitation and thus radiated noise, which can be critical for military applications, but it also offers reduced fluctuating hull-pressures and propeller induced vibrations at the stern; having particular advantage for ships carrying passengers.

As stated above, a further advantage when using the puller-type arrangement is the rotational energy gain presented by the pod-strut. Rotational energy in the propeller race may be reclaimed using the flow straightening effects of the strut and fins. However, it should be kept in mind that optimising the pod-body to reduce cavitation on the body surface will, by definition, reduce the rotational energy gain. Curving the strut-form (twisted strut sections) to mirror the propeller wake flow vectors can reduce suction peaks but in doing so reduces the flow straightening effects.

Pusher-type pod can still benefit, to some extent, from a decelerated flow; offered by the pod-body wake field. However, this wake field can have a sharp variation due to the pod-strut wake shadow; leading to unsteady flow effects, local cavitation and related consequences. The pod-body does presents less frictional drag, as the flow field is not yet accelerated by the propeller, but the slower flow makes it a less powerful control surface. Thus, most of the advantages available to the puller-type pod are not applicable.

Double-ended pods use a propeller at both ends in tandem (both propellers rotating in the same direction). The advantages and disadvantages presented for either the pusher- or puller-type pods can be rationalised on a case-by-case basis. Nevertheless, the main advantage of the double-ended configuration is when draught limitations exist. Transmitting the same thrust through two smaller propellers presents efficiency losses but with careful design these can be minimised; offering a compact and shallow draught pod solution. Furthermore, suitable guide-fins fitted to the pod-body can be used to further recover rotational energy from the front propeller while guiding a favourable flow onto the rear propeller; further improving the unit efficiency.

10 Seakeeping and Stability

The main problem with generalising arguments related to seakeeping is in deciding whether to compare like-for-like solutions or comparative optimal solutions. Nevertheless, neither method seems to raises any alarming differences between conventional propelled and pod-driven ships; Sarioz (2004). Notwithstanding, some key differences should be observed when modifying the design of a ship to include pods. Firstly, the pods themselves contribute a significant local mass, the prim-movers are relocated, and the space/cargo arrangements reorganised. These changes can have significant impact on the moments of inertia of the ship and thus its dynamic behaviour. Second, the prammed stern may present a higher than normal risk of adverse slamming behaviour. While this may sound alarming, only isolated cases are reported and then only when operating at slow speed or at rest in harbour. Attention at the preliminary design stage can help to minimise any adverse slamming risks. Lastly, the large control force afforded by the pods can result in large snap-rolling angles when initiating a turning manoeuvre. Figure 6 gives an example of the snap- rolling experienced by a pod-driven Ropax when initiating a 35 degree helm turn. While careful attention to the manoeuvring behaviour can be used to minimise any peak forces, designers should make themselves aware of specific snap-rolling limiting criteria give by the regulative bodies or classification societies.

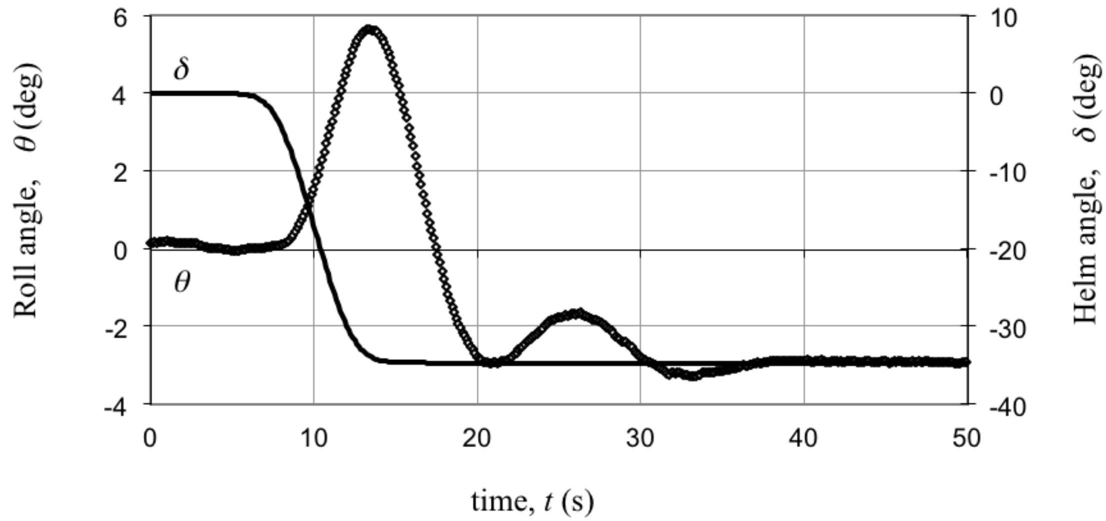


Fig. 5 – Example of snap-rolling behaviour

11 Electric motor selection

Generally speaking, there are three main motor topologies, Lainè et al. (2005). The transverse flux topology is found to be less than attractive due to its complex construction. Also, axial field topology is better exploited with larger diameter, shorter length motors; in direct conflict with the hydrodynamic optimum for pods. The radial flux topology is found to be commonly used for all types of applications and lends itself well to the characteristic shape of the pod-body. For the choice of energy conversion there are again three current options: conventional wound synchronous motor; induction motor; permanent magnet synchronous motor. In addition there is a future option of using high temperature super conducting motor. Of the current options, the permanent magnet synchronous motor offers the most advantages in terms of power density, reliability, noise and vibration.

For motor cooling requirements, conventional wound synchronous motor generally use forced air cooling. Forced convection sea water cooling may be a better solution for the permanent magnet synchronous motor but some uncertainties are still apparent regarding heat transfer rates from the pod-body. However, to further improve the situation, an auxiliary forced air system may help in critical areas. Also, the introduction of a fresh-water cooling-system may be employed; removing the issue of heat transfer through the pod-body.

In general, motor capacity is approximately proportional to the square of the rotor diameter but only linearly proportional to the length. As the hydrodynamic efficiency increases with the propeller/body radius ratio, then clearly, the optimum motor and hydrodynamic performance are in conflict.

In an attempt to address this conflict, a Rim-Driven Pod (RDP) concept was developed with the motor in a duct around the propeller. The concept comprises of a multi- blade row propeller with a permanent magnet radial flux rotor mounted at the blade tips. The stator is sealed from the water inside a cylindrical duct, which surrounds the propeller. The configuration is much shorter in length in comparison to a conventional pod (about a third the length) but with the same power and providing other hydrodynamic advantages.

For the more conventional pod configuration, further reductions in the motor size for the same motor power may be possible using high temperature superconducting motors. Nevertheless, while military applications are under investigation, commercial applications may take some time to reach the market.

12 General Arrangements

Generally speaking, choosing an ACD solution should offer some quantitative measure in the form of a weight saving. The removal of long propeller shafts, reduction gearboxes and other auxiliary equipment can provide a reduction in net mass which can be directly offset by an increase in payload for the same overall displacement. However, the qualitative merits are a more apparent when assessing the benefits to space arrangements. For units with electric motors, the relative proximity independence of the prim-movers, offers great flexibility with respect to the internal space arrangements. Generators, connected to the ACD's only by electric cabling, can be located more conveniently for maintenance access. Also, exhaust conduits can be organised so as not to interfere with open car-decks or passenger spaces. The freedom with prime-mover location can also offer greater flexibility when it comes to choosing the location of the superstructure; no longer is it strictly necessary to place the accommodation block, engine room and propulsion units all together simply to better prioritise other more cargo friendly space. Figure 6 gives a comparison of two optimal designs addressing similar missions; one designed with a conventional propulsion arrangement (top) and one designed with azimuthing pods (bottom); Rosendahl (2005). Further, for passenger ships, the reduced propulsion induced vibration can offer more profitable space solutions; with a more optimal use of the stern part of the ship.

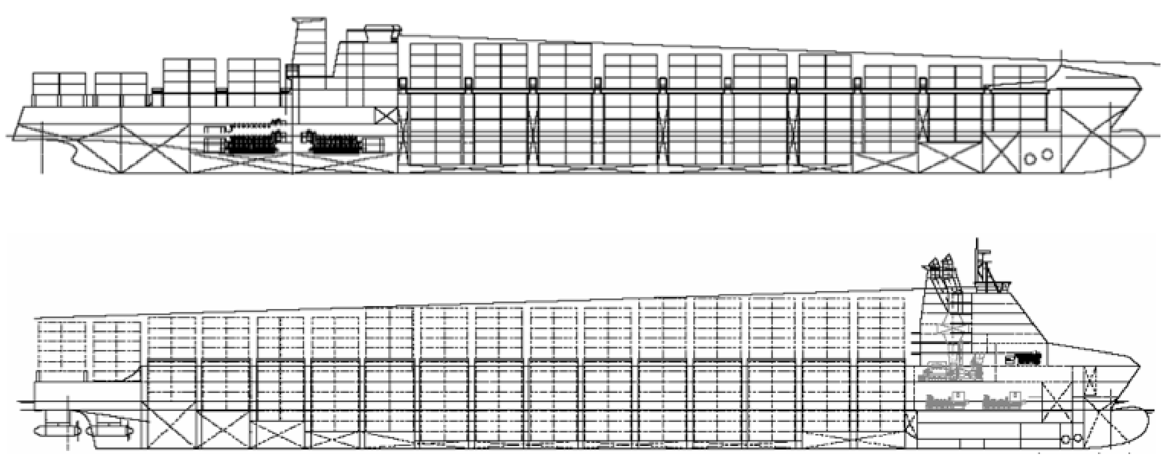


Fig. 6 – Example of the change in general arrangements

13 Mission matching and economics

Further to the increased safety and reduced berthing costs, there can be a significant fuel saving. Most ships operate to a predefined schedule, so time saved in port can be directly offset by a reduction in sea speed for the same overall turnaround time. As the ship resistance is approximately proportional to the square of the velocity then, even a small reduction in the sea speed can result in a marked reduction in fuel usage; offering both a reduction in cost and environmental impact. It is worth noting that speed restrictions imposed by the port authority may impact on any advantages. Conversely, an ability to leave the quay in otherwise adverse beam wind may improve operability. Considerations such as this, together with other location specific issues, should be looked at in detail to inform correctly the decision to opt for ACD's over other control arrangements.

The main disadvantage of the azimuthing pod-drive concept is the initial costs. In fact, in a cost comparison study, the total pod system costs are found to be on average €12 Million more than the convention system, for comparable large commercial vessels, regardless of type; Andersson (2002). It is argued that this cost increment is as applicable to a €100M Ropax as a €400M Cruise ship. The study finds that, based on fuel saving alone, the payback period is 18 years; which is far in excess of the accepted limits. However, no account is made of the other qualitative or quantitative advantages when using the technology. Clearly, the rapid uptake of the technology would indicate that profit margins are in fact attractive.

In the early days, some arguments were put forward suggesting that the pod solution could offer reduced crew; typically needing one less motor man. In practice, it is now generally accepted that the motor-man has in fact been replaced by an electric motor specialist. However, the move to a more modularised machinery arrangement can offer a better routine maintenance program which, ultimately, should lead to better overall maintenance cost efficiency.

14 Ice applications

While the pod solution may initially appear vulnerable to damage in ice, they are now well proven in service. In fact, the original concept for pods was devised as a solution for ice breaking ships. The ability to provide a control force even when at a dead stop is invaluable to the operation of this type of ship. Further, many ice breaking ships serve a duel mission, clearing channels in the winter and acting as harbour tugs in the summer. And, the lower levels of course-stability and high levels of manoeuvrability, characteristic of the pod solution, are appropriate for both these types of mission.

A more recent innovation for ice applications is the development of the Double Acting Tanker (DAT). These ships also have duel mission requirements; splitting there operating time between open sea and ice. When in the open sea the tankers operate very much as with a normal pod-driven ship; with a bulbous bow optimised for open water performance. However, when entering the ice the pod is swung through 180 degrees, allowing the ship to go astern with the propeller still operating in the correct sense of rotation. The stern of the ship is optimised as an ice-breaking bow without significantly reducing the open sea performance.

While one may be initially concerned by the idea of the ship entering the ice 'propeller first', this in fact results is less propeller/ice impacts than if the propeller were at the back of the ship (with respect to direction of travel). The deep submersion of the propeller means that it has good clearance when the ice sheet is first broken. However, as the now broken ice moves astern, it is dragged deeper by the more turbulent flow, where it is more likely to impact a propeller located at the stern. Notwithstanding, in thick ice it is possible to use the pod propeller to mill through the ice; the additional load of which can be well accounted for.

15 Fast ship applications

The objective of one European Community sponsored research projects [FASTPOD] was to identify the maximum feasible limits when using pods on large and fact commercial ships. Two possible missions were examined including the trans-Atlantic transportation of containers, aiming for 35 knots, and a Ropax servicing Mediterranean routes aiming for 38 knots. The study found that pods could be adapted to propel fast ships in a safe and efficient manner.

The main advantages include good manoeuvrability and good cavitation performance. Even though the ship designs were inherently very course-stable due mostly to their long slender form, the pod still provided very good manoeuvrability. The more uniform wake field provided very good cavitation performance, often difficult to achieve with similar conventionally propelled fast ships. Also, the good cavitation performance leads to good noise and vibration performance and favourable pressure pulse characteristics.

The main point for attention at the preliminary design stage was found to be the pod locations. Each design has four pods, which were difficult to arrange without either mechanical interaction or protrusion from the hull side when slewed. Also, some efficiency losses are observed if the wake from the forward pod interacts unfavourably with the pod behind it.

A second point for concern was the large manoeuvring induced loads developed by the control pods. However, the good course-stability of the hull-forms helped to reduce the acceleration dependant dynamic loads. The structural analysis study found that no undue problems were encounter in dealing with the loading; stresses were found to be acceptable using a practical structural arrangement.

For high-speed applications, large propeller loadings may lead into unacceptable levels of cavitation both at the propeller and the pod-strut, particularly in off-design conditions including small slew angle. It is therefore recommended to include steering-flaps for course-keeping; instead of slewing the pods.

Finally, the main limiting factor was found to be the total hydrodynamic efficiency of the pods due to the size of the electric motors. The propeller to pod-body diameter ratio can be critical for the success of these high-speed designs and careful attention is thus warranted for this area at the preliminary design stage. The future development of superconducting motor technology may help in this respect.

16 Summary and conclusion

Generally speaking, the power-range and variety of ACD’s applications, and specifically, azimuthing electric pod drives, demonstrates continued growth; which would indicate market satisfaction with the products. It is not entirely unrealistic to surmise that pods have reached a technological maturity; ultimately leading to their wider use.

Until now, pods have been most commonly used on cruise ships and ice breaker applications however they are entirely applicable for a great many other applications. The modifications in the stern-form can offer better use of space for car decks and the manoeuvring performance is quite suitable for the typical mission profile of Ro-Ro and Ropax applications. Also, while the good manoeuvring performance is most attractive for missions with substantial harbour operating time, the pod solution is shown to be equally applicable for long haul routes; including fast ship applications. Pods can offer advantages for high-speed applications but careful attention must be given to find the optimal balance between motor-size and hydrodynamic efficiency as well as to cavitation performance.

The main advantages offered when using pods is the improved manoeuvrability and propulsive performance. However, it is also shown that pods experience significant spike loads that are in origin related to dynamic manoeuvring. Consequently, it is recommended that the preliminary design be as course-stable as possible; reducing acceleration dependant loading and assuring good course- keeping behaviour.

For the pod structure and more specifically the bearings, it is important to consider the gyroscopic precession loading. For the structural analysis, stress concentrations factor methods are found to provide unreliable results due to complicated loading patterns and three-dimensional effects. Consequently, a finite-element analysis using a global-local technique is recommended.

One final qualitative advantage of the pod solution is identified as the greater flexibility with the general arrangements. This can have significant impact on both the space arrangements and the redundancy capacity of the ship. With the application to a wider range of ship-types and with increasingly innovative designs, it is certain that we will see many new varieties of efficient and profitable pod-driven ships in the coming years.

17 References

WIPO, Azipod, World Intellectual Property Organization. International Bureau, WO 0 590 867 A1 (1992).

van Blarcom, B., Franco A., Lea M., Peil S., van Dine P. and Thompson D., Rim-drive propulsion – Improving reliability and maintainability over today's pods, T-POD, 14-16 April, Newcastle University, UK (2004).

OPTIPOD, Optimal design and implementation of azimuthing pods for the safe and efficient propulsion of ships - Annex 1 (Description of work), European Commission RTD FP5 project, GRD1-1999-10294 - Chantier's de l'Atlantique [Co-ordinator] (2000).

Pods in Service, Safety and reliability of podded propulsors under service conditions, European Commission RTD FP5 project, G3RD-CT-2000-00242 - Maritime Research Institute Netherlands [Co-ordinator] (1999).

FASTPOD, Fast ship applications for pod drives - Annex 1 (Description of work), European Commission RTD FP5 project, GRD2-2001-50063 - University of Newcastle [Co-ordinator] (2001).

T-POD, First international conference on technological advances in podded propulsion, T-POD Proceedings, School of Marine Science and Technology, University of Newcastle, UK (2004).

VRSHIPS-Ropax, Life-cycle virtual reality ship sytem(s), Annex-1 (Description of Work), European Commission RTD FP5 project, GRD1-2000-25709 - University of Strathclyde [Co-ordinator] (2000).

Atlar, M., Allema, J.H., Ishikawa, S., Kim, S-E., Liu, P., Pustoshny, A., Sanchez-Caja, A., Sasaki, N. and Traverso, A., The specialist committee on azimuthing podded propulsion, Final report and recommendations to the 24th ITTC, Proceedings of the 24th ITTC-Volume II, Edinburgh (2005)

Woodward, M. D., Control and response of pod-driven ships, PhD Thesis, School of Marine Science and Technology: 225 p. (2005).

Woodward, M. D., Clarke D. and Atlar M., On the manoeuvring prediction of pod-driven ships, Int. Conf. on Marine Simulation and Ship Manoeuvrability - MARSIM'03, , Kanazawa, Japan (2003).

Woodward, M. D., Atlar M. and Clarke D., Manoeuvring induced loads on fast pod drives, Int. Conf. on Fast Sea Transportation - FAST'2005, St. Petersburg, Russia (2005b).

Konieczny, L., Development of FASTPOD design methodology - Cargo ship, FASTPOD project, European Commission RTD FP5 project, GRD2-2001-50063 - University of Newcastle [Co-ordinator] Commercial in Confidence (2005).

Sarioz K, Atlar M, Sarioz E, Woodward M.D. and Sampson R., Operability of fast podded ropax vessels in rough seas, T-POD, University of Newcastle; 14-16 April (2004).

Lainè, C., Letellier P., Konieczny L. and Woodward M.D., Fastpod design methodology, FASTPOD project, European Commission RTD FP5 project, GRD2-2001- 50063 - University of Newcastle (Co-ordinator) Commercial in Confidence (2005).

Bretz, E.A., Super Conductors on the High Seas, 23rd IEEE Spectrum, January NA (2004).

Rosendahl, T., Design iteration, integration of FASTPOD design characteristics, FASTPOD project, European Commission RTD FP5 project, GRD2-2001- 50063 - University of Newcastle [Co-ordinator] Commercial in Confidence (2005).

Andersson, L., Total cost comparison between podded and classical Ropax - WP8-DOC-008, OPTIPOD, EU Project No. GRD1-1999-10294, Commercial in Confidence, (2002).