Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title:

Deliverable 1.1:

Review of available hydrodynamic knowledge

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EXECUTIVE SUMMARY

The aim of Task 1.1 is to review hydrodynamic knowledge with respect to the ability to model azimuthing control devices. For this purpose, available and ongoing sources of information is surveyed and compiled to form a database of existing capabilities. The main areas of focus will include:

- Determination of basic groups of interest.
- Survey of past projects outcomes and recommendations.
- Survey of existing conference series and published knowledge.
- Explore output from ongoing related initiatives and workshops.
- Discuss output from pilot associations and operators forums.
- Compile list of subject specific terminology and definitions.

Determination of basic groups of interest is reported by means of a data base covering the different groups from developer and manufacturer to operators and ship owners. The groups of interest are also reflected by a survey of ships equipped with different types of azimuth propulsion (APPENDIX 1). This statistic shows the expansion on the segment of ships with azimuth propulsion.

A detailed description of the European project and theirs outcome is reported in APPENDIX 2. This report includes general description of the three major European project, Pods-in-Service, OPTIPOD and FASTPOD. The outcome of tow latter project has been in detail described and gained hydrodynamic knowledge specifically related to azimuth propulsion is highlighted. There are very few public reports from Pod-in-Service and therefore this project is only briefly described. In addition to the European frame work project and number of other projects worldwide are described in chapter 3.

An extensive survey of existing conference series and published paper has been carried out and is reported in appendix 3. The report includes list of relevant conference series and their related papers. Each paper is categorised in terms of area of knowledge. This area includes:

- Manoeuvring prediction
- Propulsive performance
- Operational- and Human factor aspects
- Marine engineering

Each paper is described by a short synopsis. The report presently contains 90 papers origin from five different conference series. This list will during the project be continuously updated with new material.

A survey of ongoing activities on the area of azimuth propulsion has been carried out and is reported in chapter 5.

1 INTRODUCTION

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- Discuss output from pilot associations and operators forums.
- Compile list of subject specific terminology and definitions.

Major part of these tasks is reported in sub-report referenced by appendix 1, 2 and 3.

2 BASIC GROUPS OF INTEREST

The groups of interest have been identified by contribution of all partners in the AZIPILOT partners. This information is compiled in a document that is continuously updated during the project. This document (Basic groups of interest + shipping companies.xls) contains the following sections:

- Simulator Manufacturers
- Simulator Facilities
- Description of ACD Types (Azimuthing Control Devices)
- Ship Types
- Test Facilities
- Shipping Companies
- Pilot Organizations

The groups of interests have also been identified by listing major part of existing ship with azimuth propulsion (See Appendix 1). This includes a compilation of in total 67274 ship where 4639 (7 %) are equipped with azimuthing propulsion. The list is divided into several groups of ship types where the ACD ships are shown in diagrams on basis on installed power, length over all and year of construction.

3 SURVEY OF PAST PROJECTS

There have to date been three medium sized projects, funded under the EU framework program, that have focus on azimuthing control devices (ACD). More specifically, the three projects in question considered the design and operation of pod driven ships. Namely: Pods-in-Service; OPTIPOD; FASTPOD. Each project had a significant proportion of its work dedicated to the investigation of the manoeuvring behaviour of such ships and it thus relevant to this study.

In addition to the mentioned European framework project, some other project is reported by the ITTC The Specialist Committee on Azimuthing Podded Propulsion (ITTC, 2008a):

- A four-year R&D project was started in 2006 at SVA (Potsdam, Germany) on innovative high-efficiency pods based on the High Temperature Superconductor (HTS) technology.
- In 2005 a long term research programme has been initiated by the Italian Ship Model Basin INSEAN) with the aim of developing theoretical and experimental tools that may be used to investigate hydrodynamics and hydro-acoustics of podded propulsor.
- The EU initiative HTA (Hydro Testing Alliance) with the main objective to develop structures for definition and introduction of novel measurement, observation and analyses technologies for hydrodynamic (scale) model testing environments. This programme also includes research with the main objectives of improving model testing techniques for azimuthing pods.
- In Canada a 5 year national research programme on podded propellers was completed in 2007 and undertaken jointly by the Ocean Engineering Research Centre at Memorial University of Newfoundland (Islam et al. 2007). The aim of this project was:
    - quantify the effect of propulsor
    - computational methods for performance prediction
    - quantify the blade loading in different operational conditions including ice
- “Super Eco-Ship”, finalized in 2005 by the Japanese Government in collaboration with the National Maritime Research Institute (NMRI) and Nakashima propeller. Among other thing this project included research on CRP pod (Contra Rotating Propeller) (Kano et al. (2006)).

A detailed description of the European project and theirs outcome is reported in APPENDIX 2. The sub-sections of the report summarise the general and more specific aims and objectives of each named project. This includes:

- Overview of relevant framework funded projects
- Technical overview past European projects
- Critical appraisal of the IMO criteria like turn circle, yaw checking and stopping manoeuvres
- Hydrodynamic Modelling of podded propulsion
- Numerical Simulation
- Technical overview
- Reliability assessment including failure mode analysis

4 EXISTING CONFERENCE SERIES AND PUBLISHED KNOWLEDGE

A separate document containing a list of published papers is prepared by M Woodward, UNEW and is included in Appendix 3. Papers are reviewed and summarised in the comprehensive list. The full reference is included together with a summarised abstract. Key words are identified and use to generate a reference index at the end of the document.

The references are taken from the following conference series:

T---POD	First International Conference on Technological Advances in Podded Propulsion, Newcastle University, Newcastle---upon---Tyne, United Kingdom, 2004.
T---POD'06	Second International Conference on Technological Advances in Podded Propulsion, L'Aber Wrac'h, France, 2006.
MARSIM'03	International Conference on Marine Simulation and Ship Manoeuvrability, Kanazawa, Japan, 2003.
MARSIM'06	International Conference on Marine Simulation and Ship Manoeuvrability, Treshiling, Netherlands, 2006.
MARSIM'09	International Conference on Marine Simulation and Ship Manoeuvrability, Panama City, Panama, 2009.

5 ONGOING ACTIVITIES

5.1 Output from related initiatives and workshops

The search on internet does not find so much information on ongoing initiatives and workshops so far, except the following two projects that seem to be the related activities.

1. Loads on Pods

An ongoing project “Loads on Pods” is carried out within a joint consortium (of 23 members) under the name of Cooperative Research Ships (CRS). The project aims to make a practical tool that helps the user to determine the loads acting on the pod unit or propeller in an easy manner in the early project design phase. The practical tool should be capable of giving answers to forces acting in propulsors in *manoeuvring* and *extreme load* conditions. The project also tries to answer to the question what is the effect of cavitation dynamics to the global forces on the pods.

Expected results include

- Practical (empirical) tools for determination of loads on pods and propellers in different operation conditions;
- Practical tools based on model test experiments supported by CFD and validated with available Full Scale information;
- GUI and code that run on Windows based PC
- Guidelines on the use and limitations of RANS codes for loads prediction

For the development and validation of the model, an extensive series of CFD calculations and an innovative series of complex model tests were carried out to measure the loads on the propeller and the pod unit. In principle the research is carried out by the members only. The research results are the sole property of the members.

2. The Propeller Forum “Propellkameratene”

10 Norwegian propeller manufacturers plus DNV, NTNU and MARINTEK were running a three-year joint industry R&D forum called "Propellkameratene" between 2004 and 2007. The objectives of the forum were to develop new and more efficient design and analysis tools and to secure long-term competence development in key areas of the discipline. The main activities of the Propeller Forum were:

- Developing and verifying new design and analytical methods, which will include a number of different propulsion and manoeuvring configurations for which industry currently lacks numerical analysis tools
- Developing methods for the analysis of propulsion and manoeuvring systems operating under various loads and for given operational profiles
- Improving design and production processes
- Developing competence and human resources at university and college level, in order to raise the level of cooperation within the sector.

By now the project should have been completed. However, due to its nature of joint industry type, very little is known about the general outcome of the project. Only a number of publications by Krasilnikov et al. are publically accessible. Among the publications, four papers are related to pod propulsions. The paper by Achkinadze et al. (2003) presents a BEM method to numerically analyse podded systems whereas the paper by Krasilnikov et al. (2003) described the application of a potential flow BEM to calculate sheet cavitation on podded propellers. Reasonable result were obtained for the case of a cavitating podded propeller in a prescribed hull wake at 3° shaft inclination and a heading angle of 20°. The application demonstrates the potential possibility of the BEM method in the meantime it reveals also the need for further improvement of BEM code.

Later Krasilnikov’s group studied numerically the interaction effects in pod propulsive system (Krasilnikov et al. 2005) and the scale effects on open water characteristics of podded propulsors (Krasilnikov et al. 2006). A coupled viscous/potential approach is applied to analyse the pod propulsive system with respect to propulsive characteristics, pod drag and propeller/pod interaction coefficients. The approach consists of a higher order panel method for propeller and a commercial RANS solver Fluent for the surrounding fluid domain. The coupling between the propeller and the RANS solver is achieved by an actuator disk in the former paper and a fan-model in the latter paper. The coupled approach gives a reasonable practical compromise between accuracy achievable and resources needed for calculations. The studies reveal a number of crucial factors to make such a computational technique successful:

- An accurate prediction of propeller performance in a given non-uniform inflow.
- Necessary to take into account the Re and roughness effects on blade section drag and lift for the panel method.
- An accurate prediction of the strut drag.

The approach was further applied to study the scale effects of the pod unit. Though lack of full scale data to validate, the predicted flow behaviour seems to be reasonable.

3. ITTC activities

One of the most active international organizations that have contributed tremendous work is the ITTC Committee. ITTC has nominated a Specialist Committees that is dedicated to Azimuthing Podded Propulsion in the last two conference periods (ITTC 2005a and ITTC 2008a). The involvement and review of the state-of-the-art development on podded propulsion will continue even in the present 26th ITTC work, but the work will be carried out in the Resistance and Propulsion Committee.

5.2 Output from pilot associations and operators forums

Issues related to azimuth propulsion are found on forums for pilot associations and other operators. Examples on topic are accident and incidents, technical description.
No specific output with special focus on hydrodynamic knowledge has been found.
This conclusion is draw from review from pilot organisations linked to IMPAs (The International Maritime Pilots' Association) web portal (www.impahq.org) and some nautical forums including The Nautical Institute.

6 LIST OF SUBJECT SPECIFIC TERMINOLOGY AND DEFINITIONS

The following terminology and definitions are mainly taken from ITTC definitions. These definitions are mostly related hydro dynamic modelling and testing. Some definition considering operational issues exists by is not reported here.

Table 1 Terminology - Calm water performance

Name	Definition or Explanation	Remark
Pusher and puller pod propulsion system	Pusher (or pushing) pod – the propeller is attached to aft end of the pod Puller (or pulling or tractor) pod – the propeller is attached to the fore end of the pod	
Resistance	The fluid force acting on a moving body in such a way as to oppose its motion	
Pod housing drag	The drag of the pod body/housing	
Propeller open water efficiency	The ratio between the power developed by the thrust of the propeller P_T, and the power absorbed by the propeller P_D when operating in open water with uniform inflow velocity V_A, namely, $\eta_0 = \frac{P_T}{P_D} = \frac{TV_A}{2\pi Qn}$	
Pod unit open water efficiency	The ratio between the power developed by the thrust of the pod and propeller as a single unit, and the power absorbed by the podded propeller P_D, when operating in open water with uniform inflow velocity V_A, namely, $\eta_0 = \frac{T^{unit-o} V_A}{2\pi Q^{unit-0} n}$	
Quasi-propulsive efficiency	The ratio between the useful or effective power PE and the power delivered to the propeller P_D. $\eta_0 = \frac{P_E}{P_D}$	
Propeller gap	The clearance between the rotating propeller hub and the stationary pod body	Fig. 1
Strut gap	The clearance between the pod body(housing) and the streamlined body made for unit open water test	Fig. 1
End plate	A horizontal plate attached at bottom of the streamlined body	Fig. 1
Gap effect	Hydrodynamic interaction in the propeller gap between the hub and the pod body.	
Propeller tip clearance	The vertical distance between the tip of the blade at 12 o'clock position and the bottom of hull. For pods, the tip clearance at off design azimuth angles can be significantly smaller than in the normal running position.	
Cavitation inception	Inception of cavitation takes place when nuclei subjected to reduced pressure reach critical size and grow explosively. It is generally described by the ambient pressure at which cavitation starts.	
Cavitation	The process of formation of the vapour of liquid when it is subjected to reduced pressure at constant ambient temperature.	
Erosion	The deformation, damage or loss of materials when an object is subjected to a cavitating flow	

Table 2 Terminology - Wake wash

Name	Definition or Explanation	Remark
Slipstream wash	Can have two meanings: (1) The flow disturbance caused by the propeller induced velocity within the propeller slipstream race; (2) the free surface disturbance due to the wash waves generated by the propeller induced velocity.	
Wash wave	The ordinary (divergent and transverse) wave system generated by a ship hull	

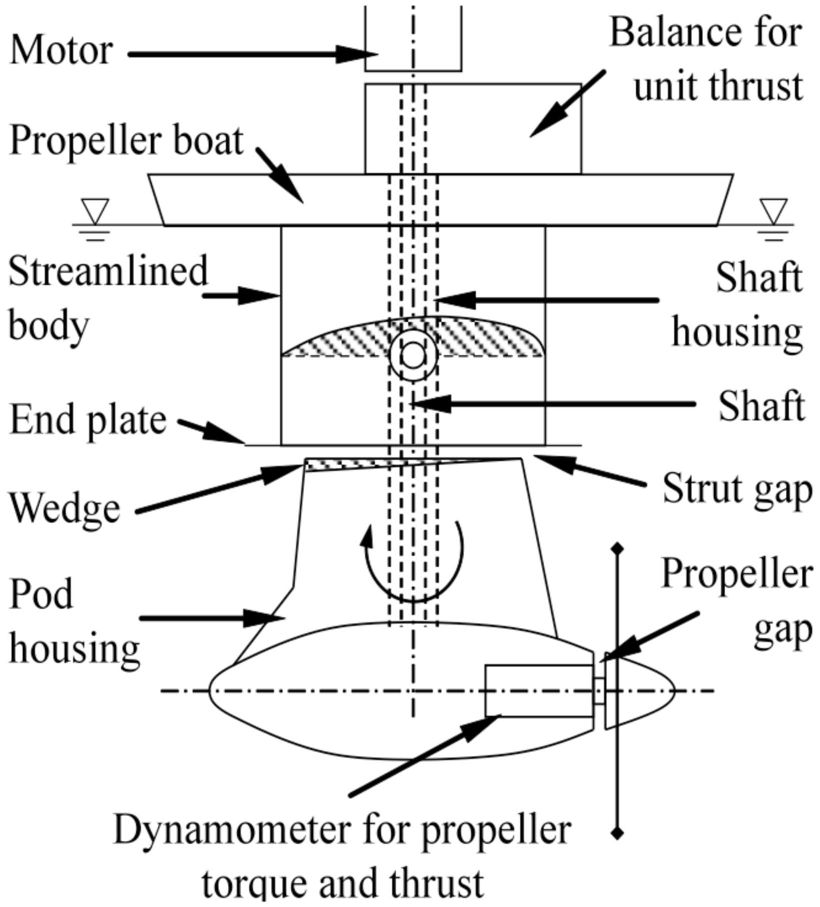

Figure 1 Terminology used in podded propeller open water test set-up

Table 3 Terminology - Manoeuvrability

Name	Definition or Explanation	Remark
Tilt angle	Inclination of pod unit in the horizontal plane from its design position	
Toe in/out angle	Inclination of pod unit in the vertical plane from its designed azimuth angular position. Toe in angle means that the rotation axis of propeller points inwards central plane, whereas Toe out angle means that the rotation axis of propeller points outwards central plane	
Dynamic stability	A body is said to be dynamically stable on a straight course or on a turn constant curvature if, when slightly disturbed	

Name	Definition or Explanation	Remark
	from a steady motion, it resume that same motion, but not necessarily along its original path, without any corrective control being applied.	
Course stability	A body is said to have course stability if, when slightly disturbed from steady motion on a straight path, it returns to its original path, without any corrective control being applied.	
Directional stability	A body is said to be a directionally stable if, when slightly disturbed from steady motion on a straight path, it returns to its original direction, but not necessarily its original path, without any corrective control being applied.	
Crash-back (or Crash Stop)	A ship manoeuvre in which, while going ahead at normal or some other speed, the propulsion devices are reversed in the shortest possible time.	
Heel or list	A steady inclination of a ship about a longitudinal axis; to be distinguished from rolling, which is an oscillatory motion.	
Manoeuvrability	Manoeuvrability is that quality which determinates the ease with which the speed, attitude and direction of motion of a body can be changed or maintained by its control devices.	

Table 4 Terminology - Seakeeping

Name	Definition or Explanation	Remark
Broaching	An involuntary and dangerous change of heading produced by a severe following sea.	
Celerity	Wave speed	
Slamming	A severe impacting between water surface and the side or bottom of a hull where the impact causes a shock-like blow	
Pounding	Described broadly as impacting between a water surface and the side or bottom of a hull. Pounding can perhaps be differentiated from slamming in that the impact, while heavy, is not in the nature of a shock.	
Slapping	A phenomenon described broadly as light impact between the water and the hull. A classification for impacts less severe than those associated with pounding.	
Seakeeping	In general, a term covering the study of the behaviour and performance of ship in a seaway. As an adjective, a term signifying a ship's ability to maintain normal functions at sea.	

7 REFERENCES

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AZIPILOT

Intuitive operation and pilot training when using marine azimuthing control devices

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Table of Contents

1 INTRODUCTION

This document is a working document for use in AZIPILOT project. The document contains statistics of ships powered by azimuth propulsion. The statistics is divided by various ship types. The source of the data is Lloyd's Register of ships. The extraction of the database contains “existing ships” according to the definition in Sea-Web.

2 OVERVIEW OF STATISTICS IN TABLE FORMAT

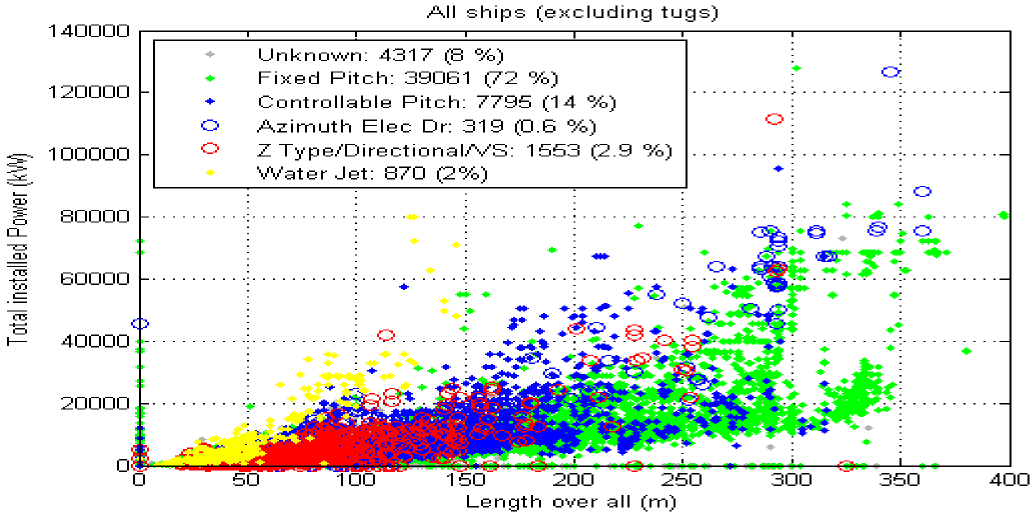
Table 1 Numbers of ship with respect to ship type and azimuth propulsion device

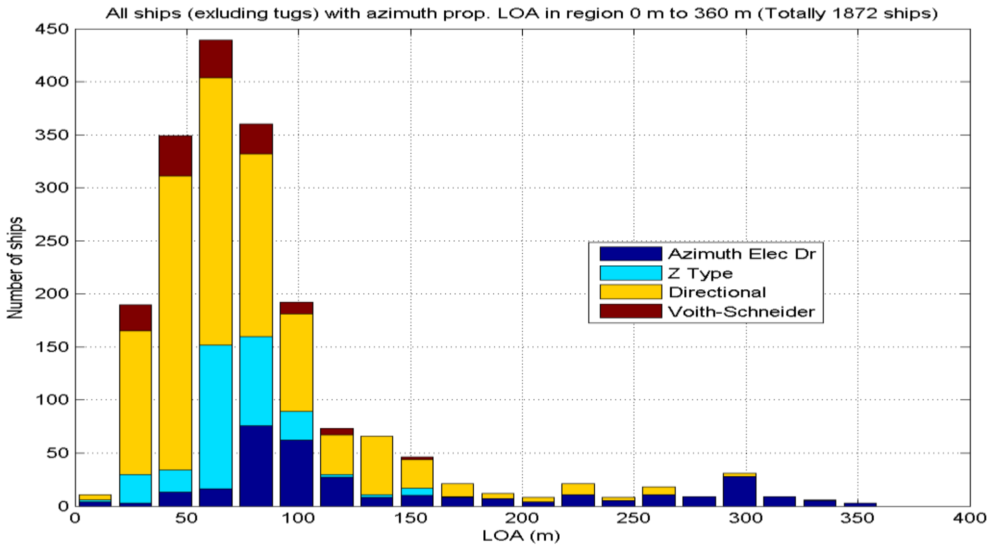
Type of ship	Numbers of ships	Numbers of ships	Numbers of ships	Numbers of ships	Numbers of ships	Numbers of ships
	Totally	Electic azi prop	Z Type	Directional	Voith-Schneider	Any type of azi propulsion
Bulk carriers	11241	0	3	12	0	15
Container ships	5898	6	0	5	0	11
Dredgers	1268	3	7	56	2	68
Inland water ways vessels	617	0	6	28	31	65
LNG-LPG carriers	1739	5	0	5	0	10
Misc vessel - Ice breaker Cabel layer etc	3346	17	28	262	17	324
Naval vessels	281	3	0	15	7	25
Offshore (other)	1084	75	21	119	8	223
Offshore supply vessels	5445	98	206	226	8	538
Dry cargo (other)	257	2	3	6	0	11
RoPax vessels	2993	20	15	185	66	286
Passenger ships	3122	3	1	53	5	62
Cruise ships	554	61	2	7	0	70
Reefer ships	1227	0	0	1	0	1
Research vessels	955	13	10	42	1	66
Tankers	13888	13	9	75	0	97
Tugs	13359	8	1113	1289	357	2767
All ships	**67274**	**327**	**1424**	**2386**	**502**	**4639**

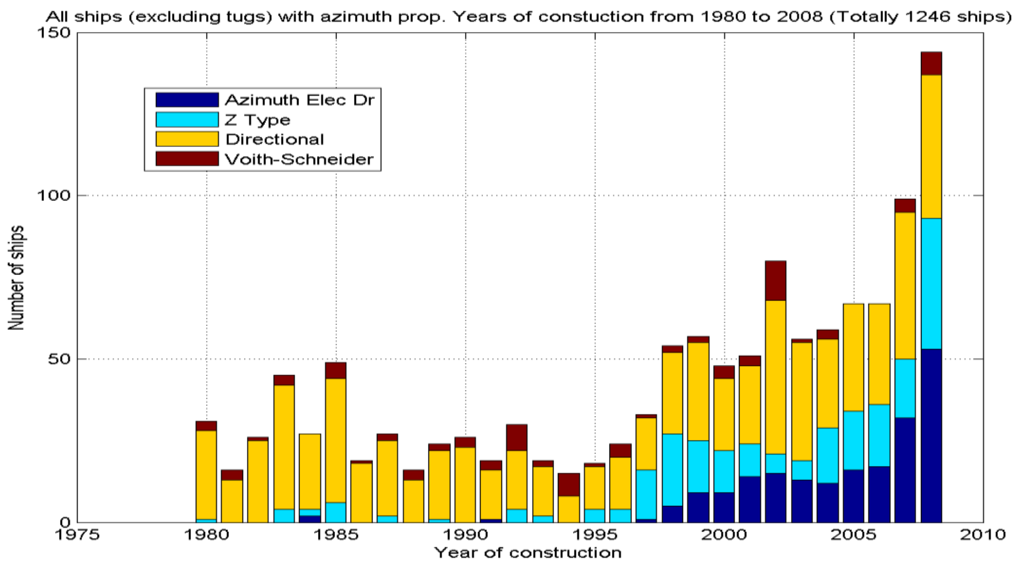
Table 2 Percentage of ship with respect to ship type and azimuth propulsion device

Type of ship	Percent of all ships	Percent of ship type	Percent of ship type	Percent of ship type	Percent of ship type	Percent of ship type
		Electric azi prop	Z Type	Directional	Voith-Schneider	Any type of azi propulsion
Bulk carriers	**16.7**	0.0	0.0	0.1	0.0	**0.1**
Container ships	**8.8**	0.1	0.0	0.1	0.0	**0.2**
Dredgers	**1.9**	0.2	0.6	4.4	0.2	**5.4**
Inland water ways vessels	**0.9**	0.0	1.0	4.5	5.0	**10.5**
LNG-LPG carriers	**2.6**	0.3	0.0	0.3	0.0	**0.6**
Misc vessel - Ice breaker Cabel layer etc	**5.0**	0.5	0.8	7.8	0.5	**9.7**
Naval vessels	**0.4**	1.1	0.0	5.3	2.5	**8.9**
Offshore (other)	**1.6**	6.9	1.9	11.0	0.7	**20.6**
Offshore supply vessels	**8.1**	1.8	3.8	4.2	0.1	**9.9**
Dry cargo (other)	**0.4**	0.8	1.2	2.3	0.0	**4.3**
RoPax vessels	**4.4**	0.7	0.5	6.2	2.2	**9.6**
Passenger ships	**4.6**	0.1	0.0	1.7	0.2	**2.0**
Cruise ships	**0.8**	11.0	0.4	1.3	0.0	**12.6**
Reefer ships	**1.8**	0.0	0.0	0.1	0.0	**0.1**
Research vessels	**1.4**	1.4	1.0	4.4	0.1	**6.9**
Tankers	**20.6**	0.1	0.1	0.5	0.0	**0.7**
Tugs	**19.9**	0.1	8.3	9.6	2.7	**20.7**
All ships	**100**	**0.5**	**2.1**	**3.5**	**0.7**	**6.9**

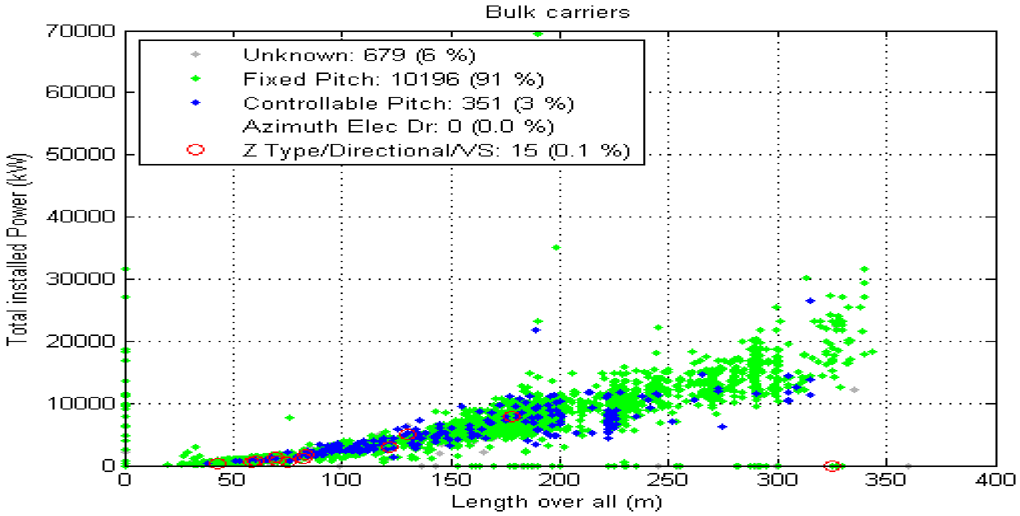
3 ALL SHIPS (EXLUDING TUGS)

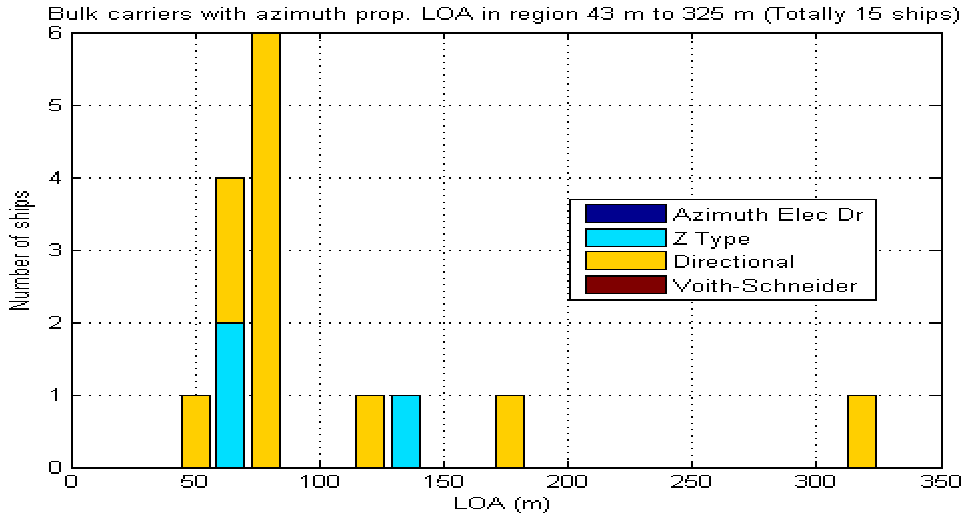


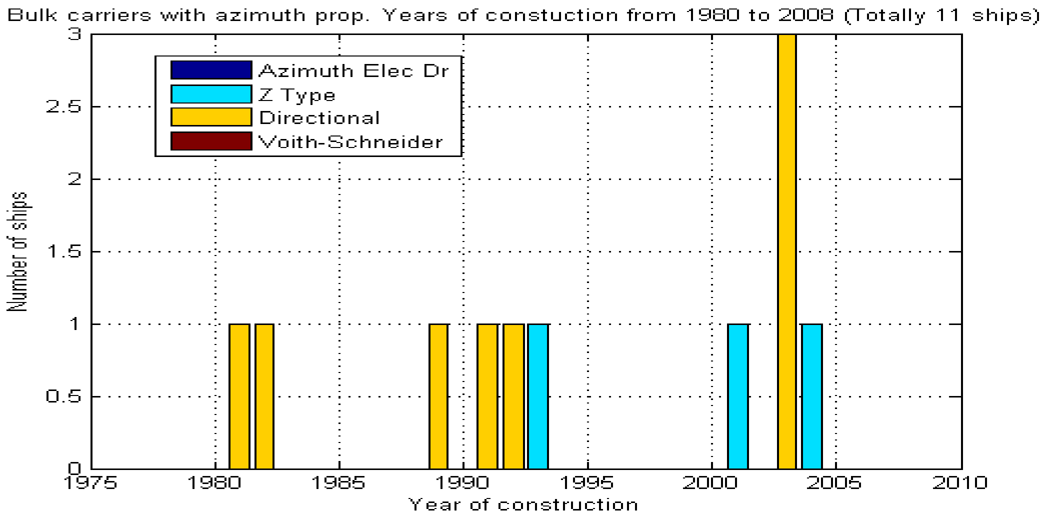




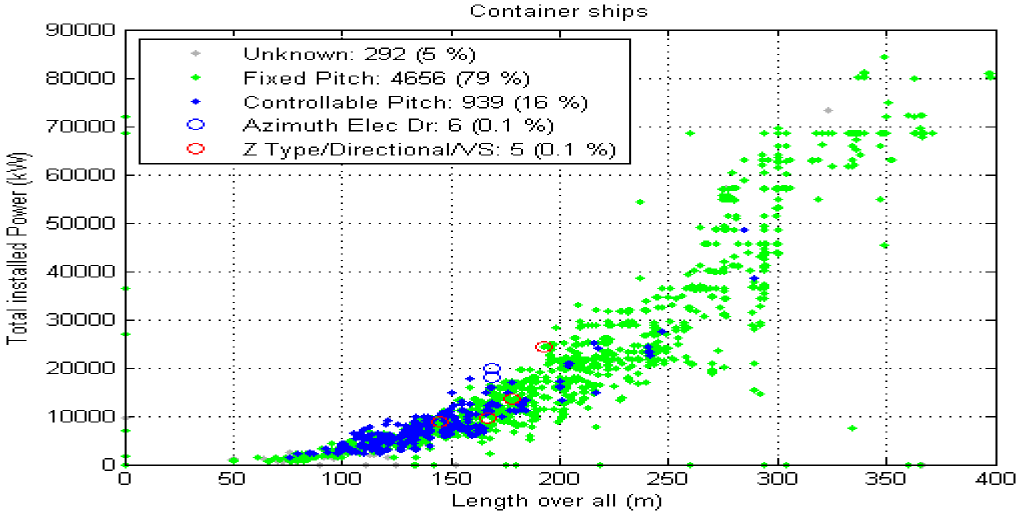
4 BULK CARRIERS

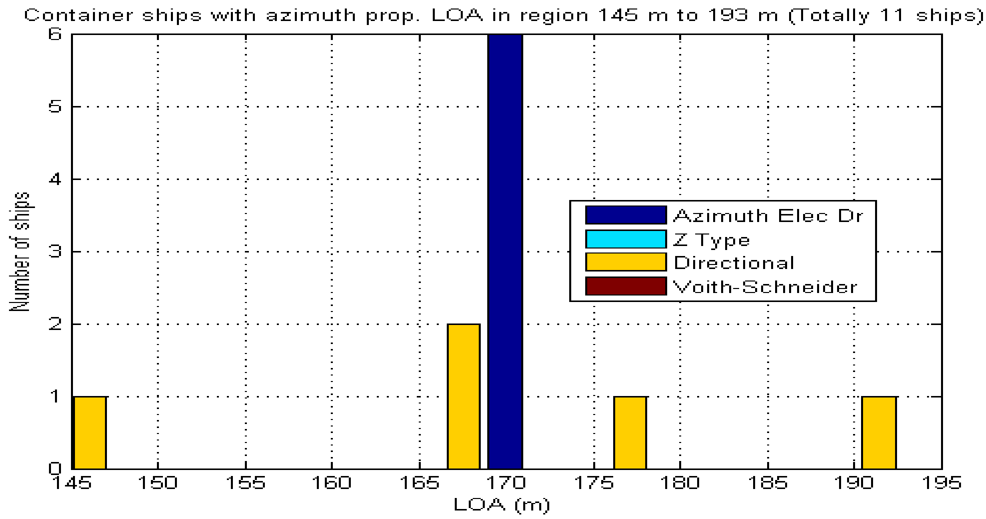


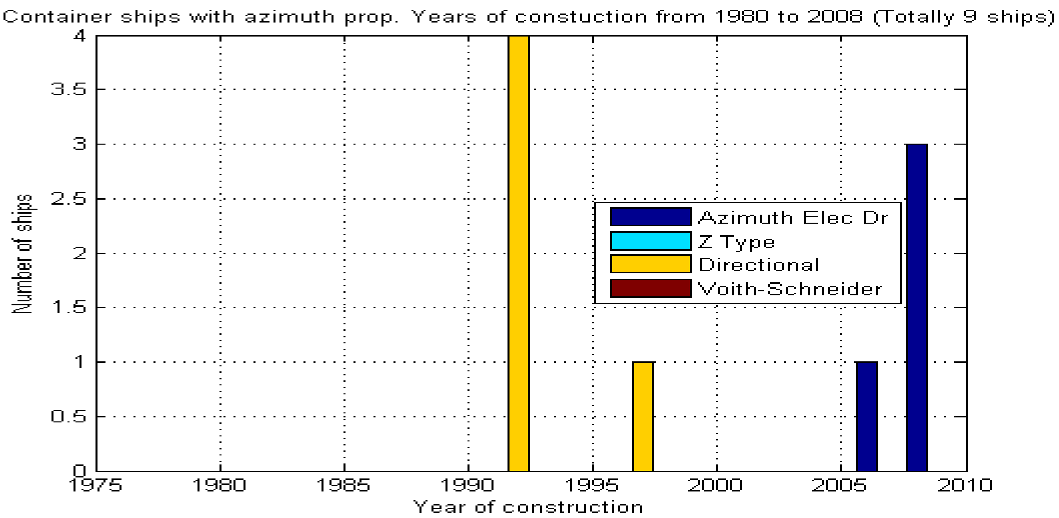




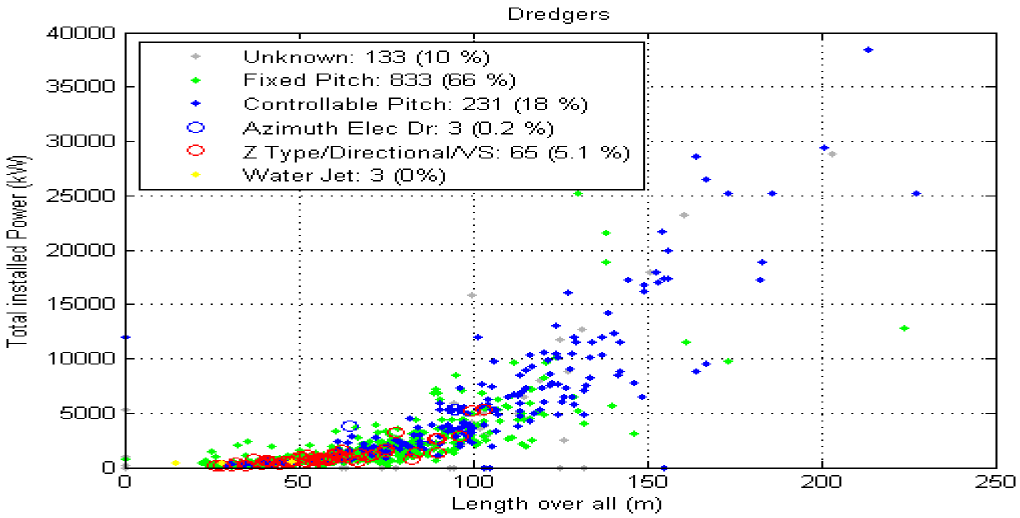
5 CONTAINER SHIPS

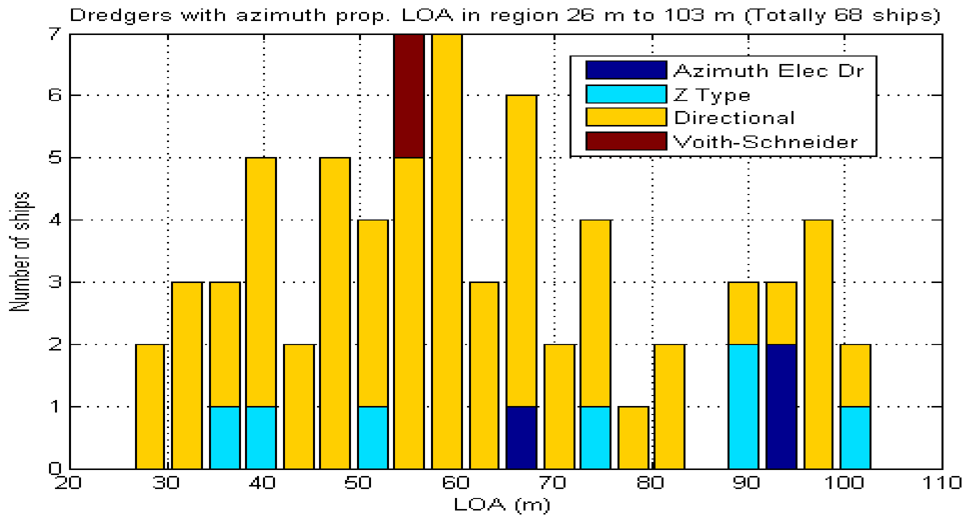


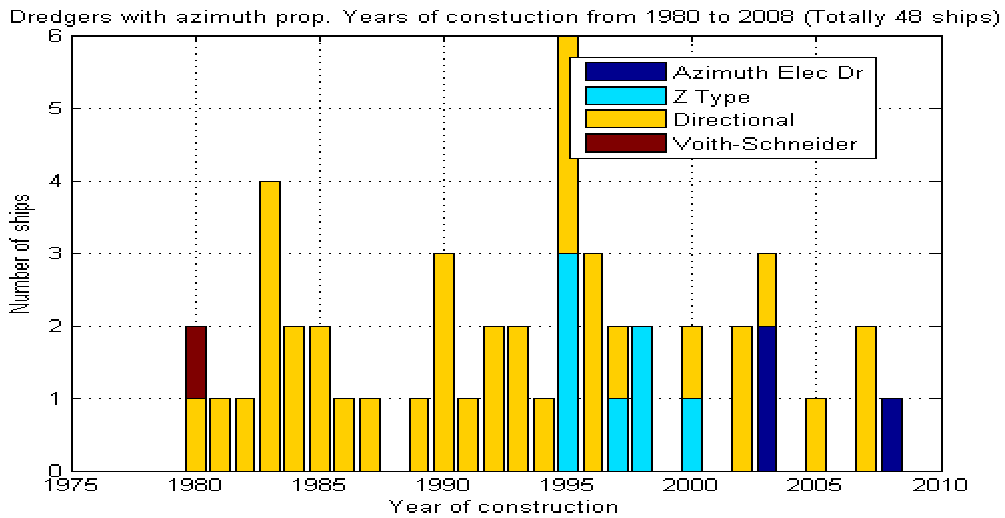




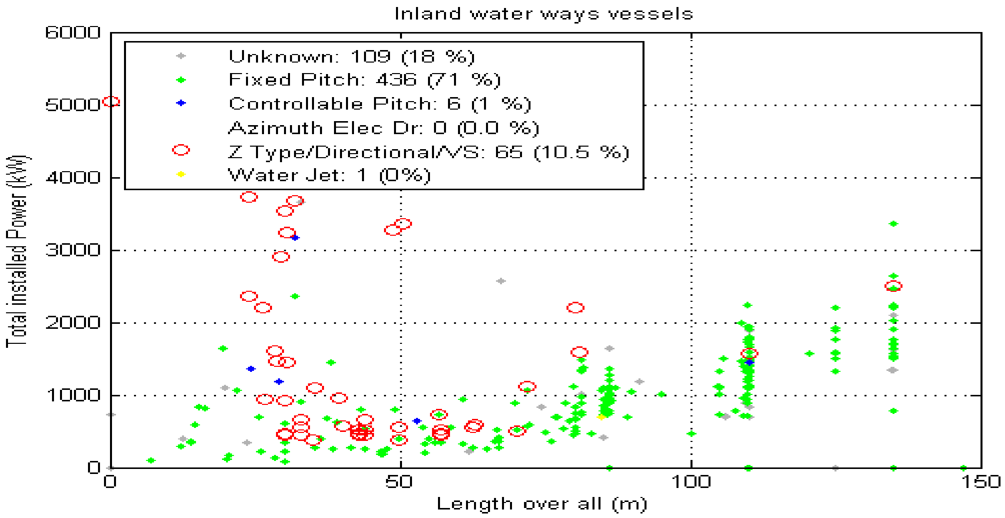
6 DREDGERS

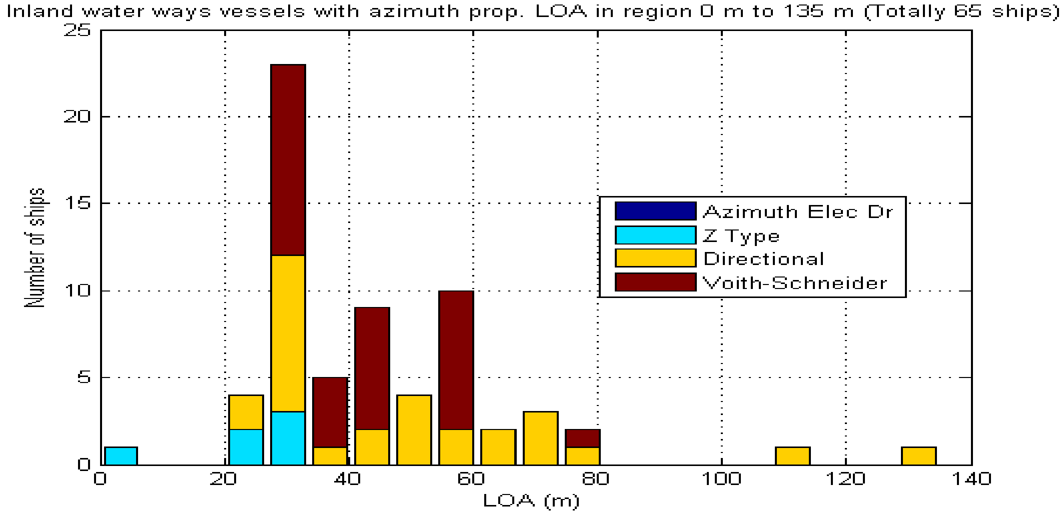

Dredgers
Unknown: 133 (10 %)
Fixed Pitch: 833 (66 %)
Controllable Pitch: 231 (18 %)
Azimuth Elec Dr: 3 (0.2 %)
Z Type/Directional/VS: 65 (5.1 %)
Water Jet: 3 (0%)
Total installed Power (kW)
Length over all (m)

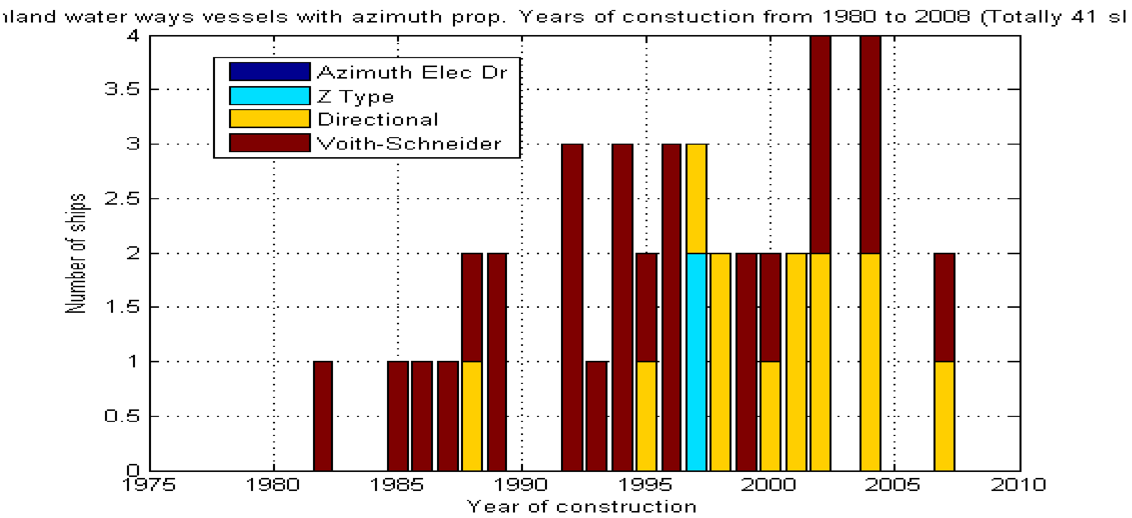

Dredgers with azimuth prop. LOA in region 26 m to 103 m (Totally 68 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
LOA (m)


Dredgers with azimuth prop. Years of constuction from 1980 to 2008 (Totally 48 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
Year of construction

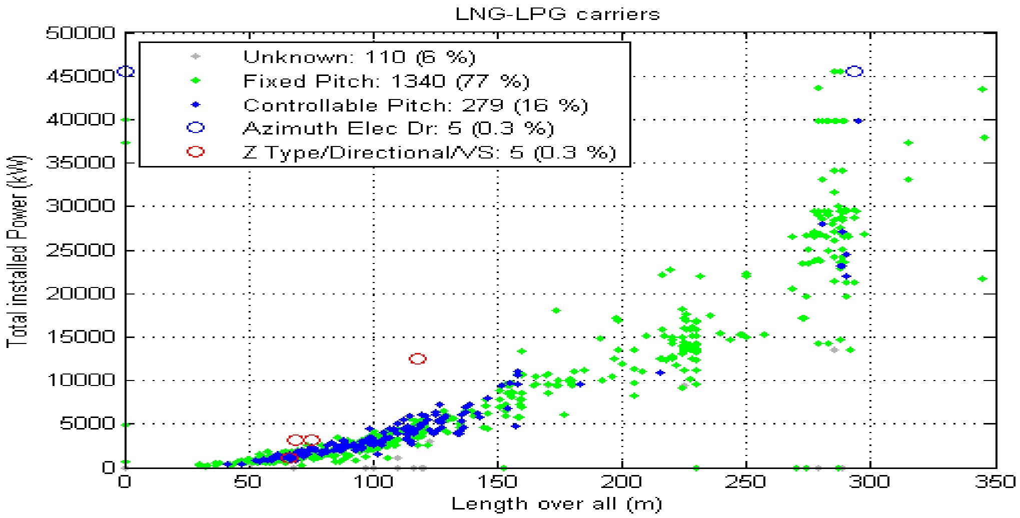
7 INLAND WATER WAY VESSELS

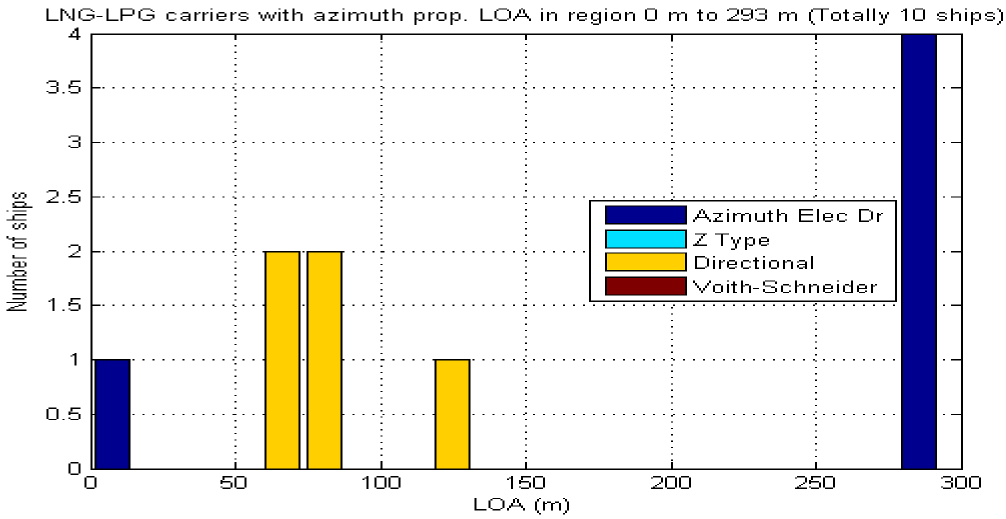


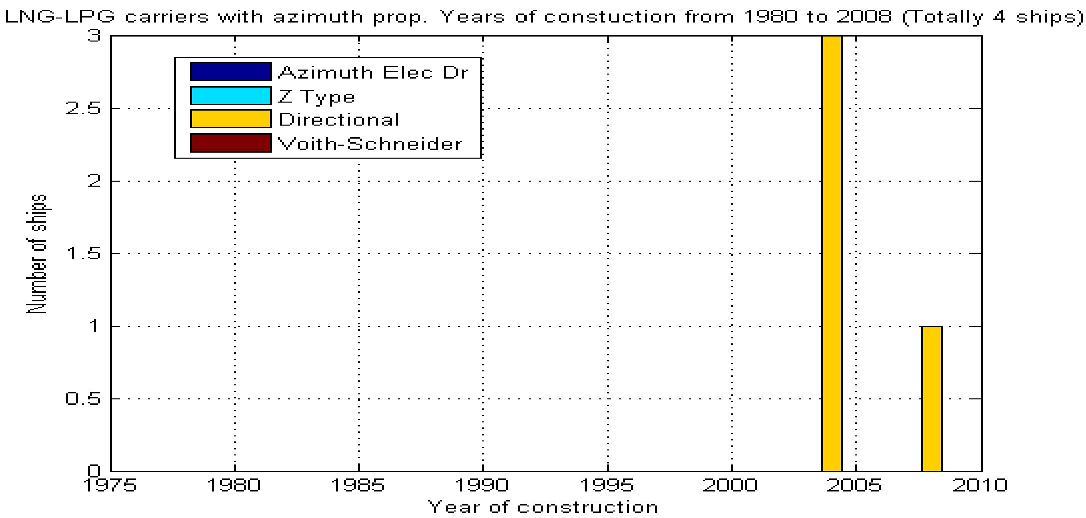




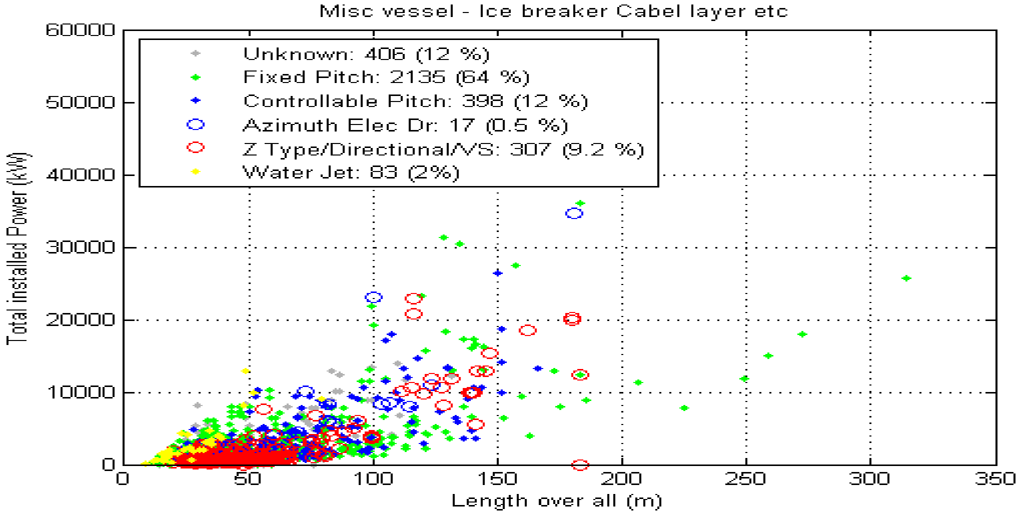
8 LNG AND LPG CARRIERS

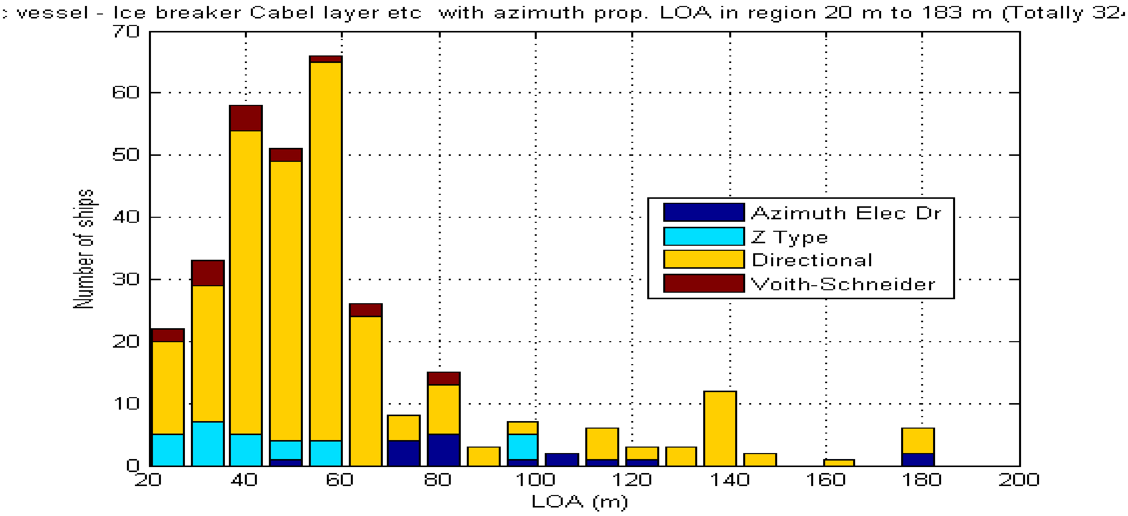


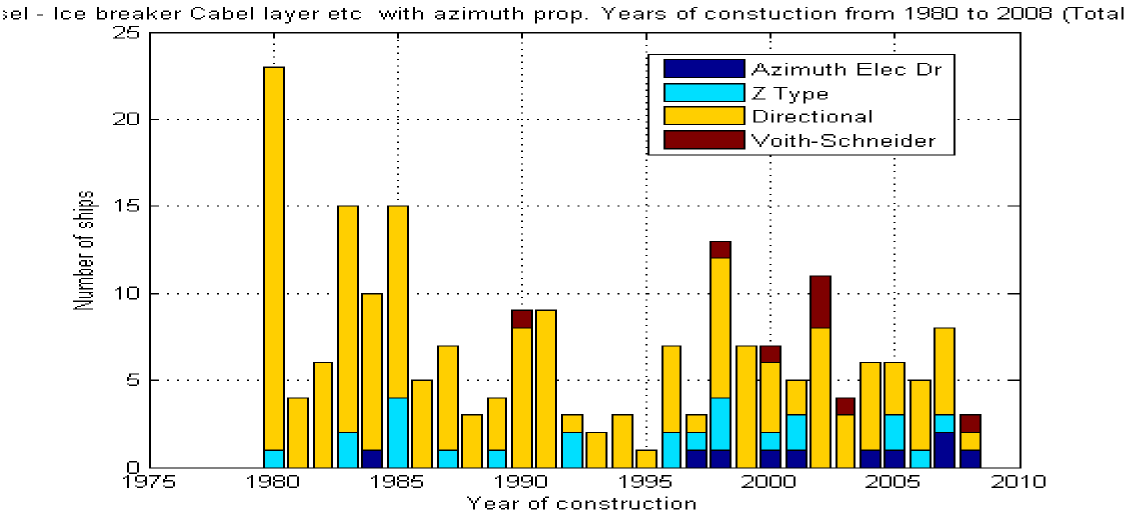




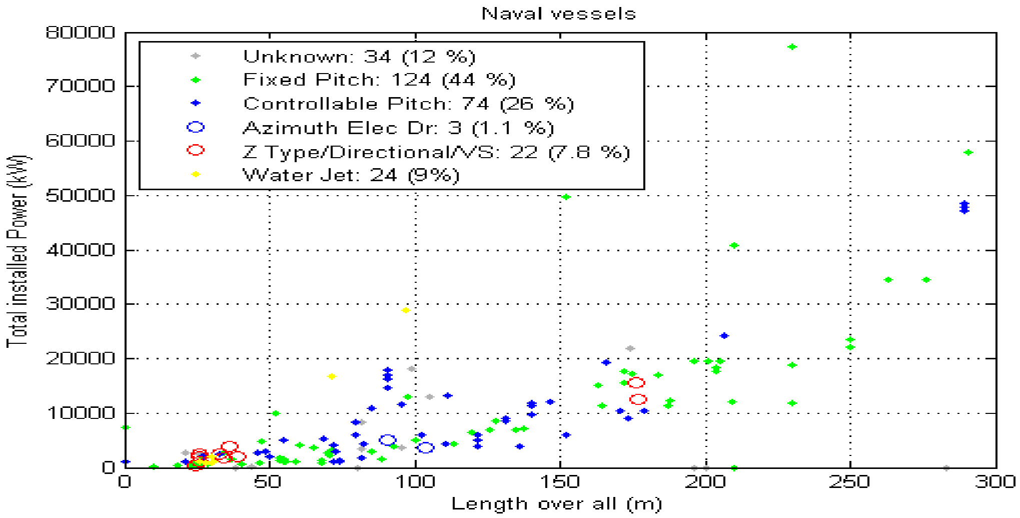
9 MISCELLANEOUS VESSELS, ICE BREAKERS, CABLE LAYERS ETC.

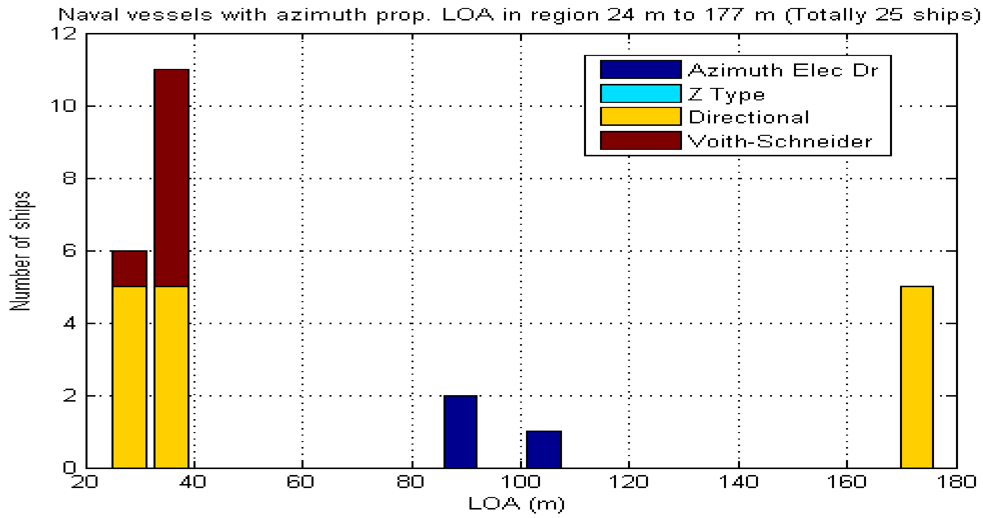


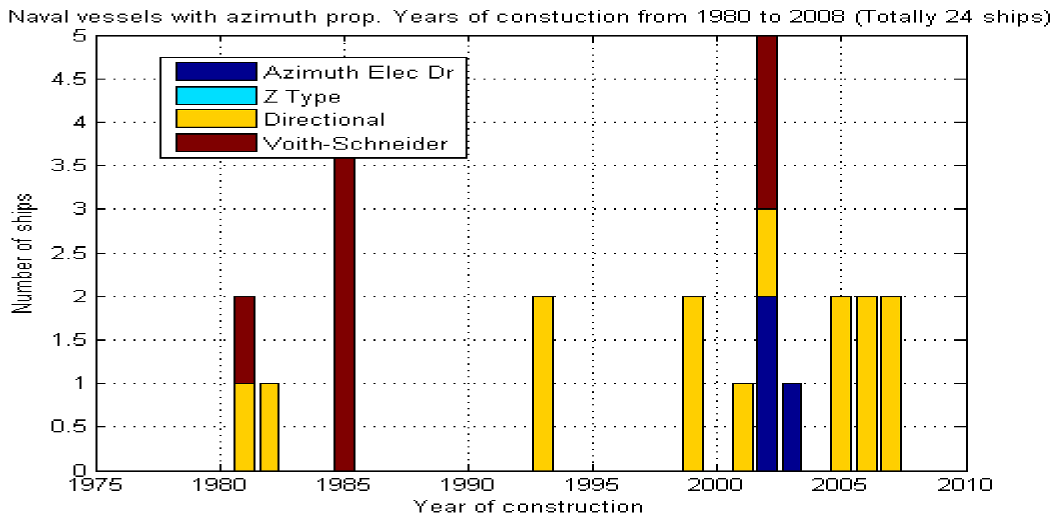




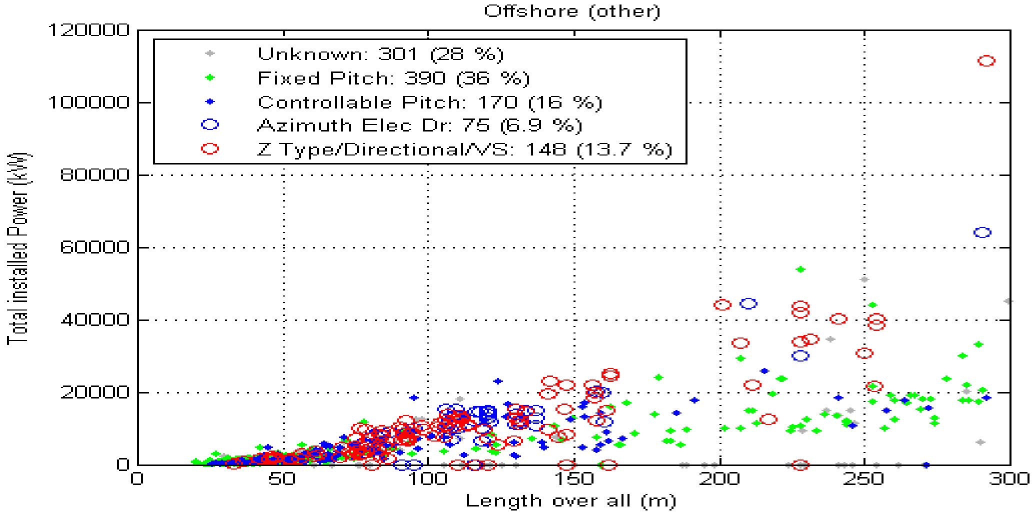
10 NAVAL VESSELS

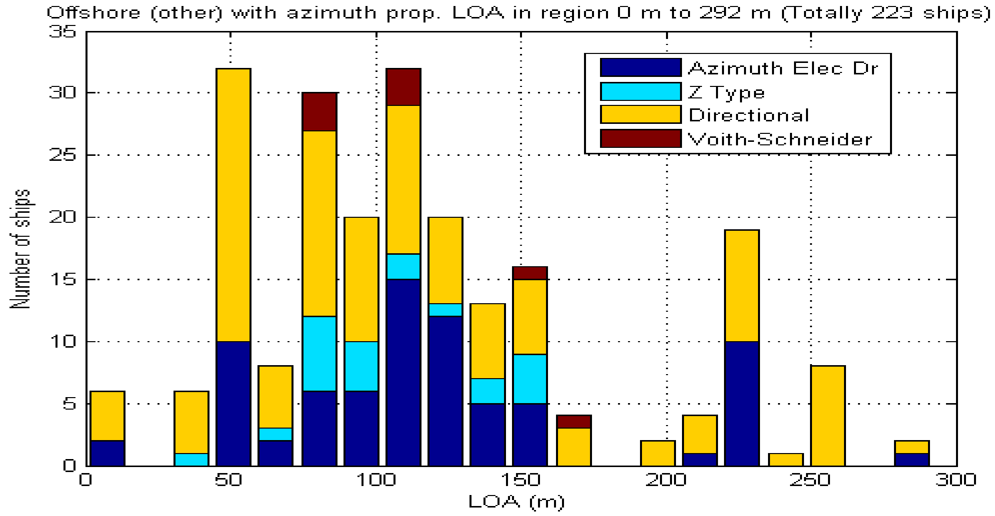


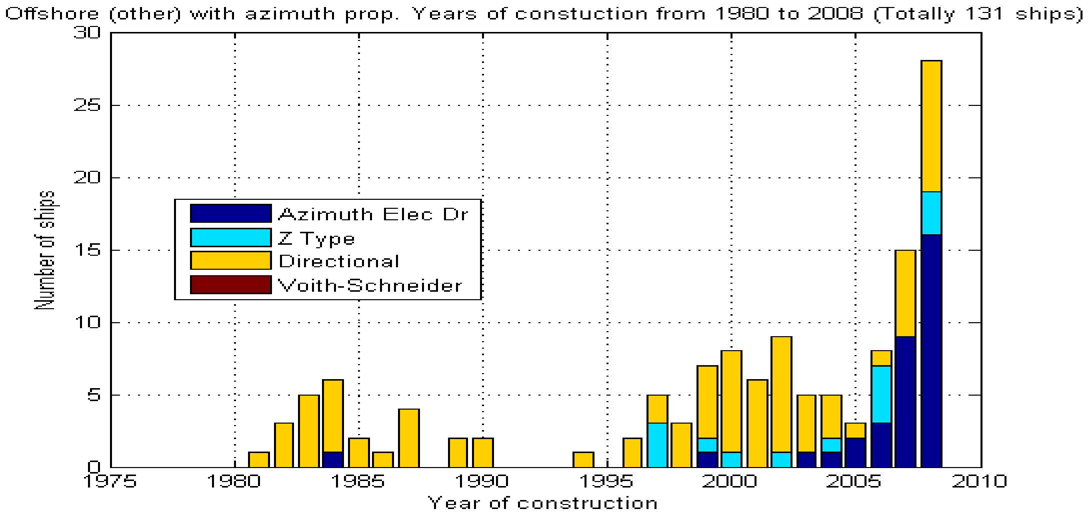




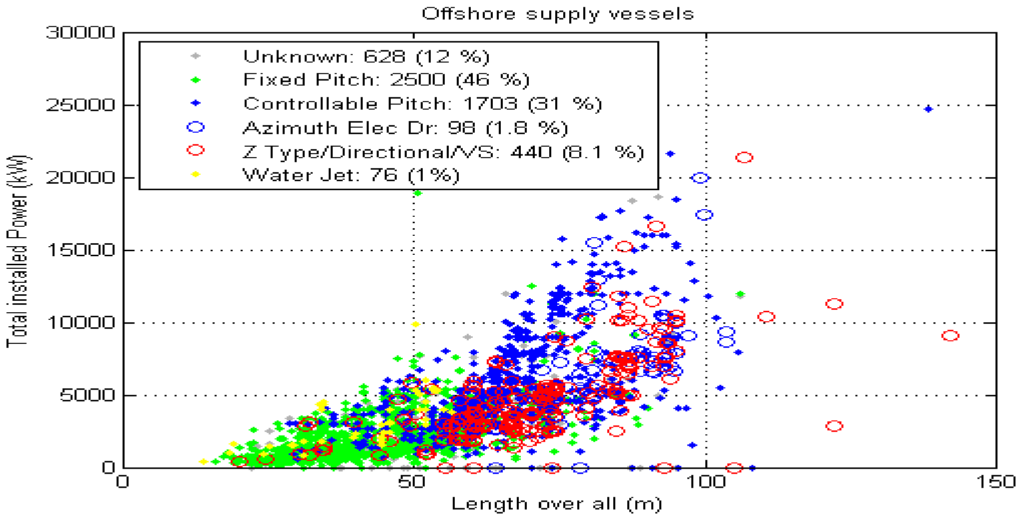
11 OFFSHORE - OTHER THAN SUPPLY VESSELS

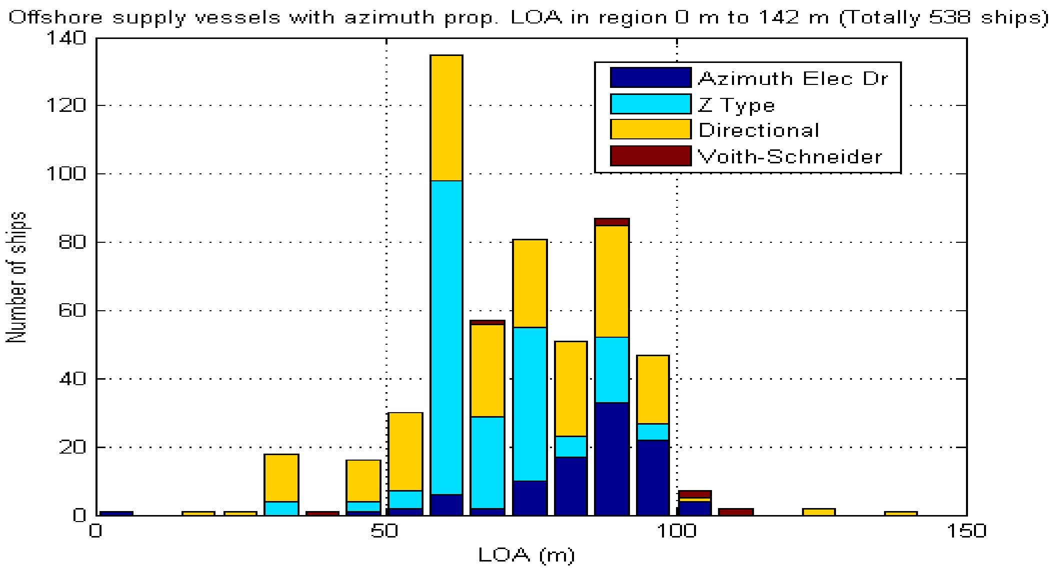


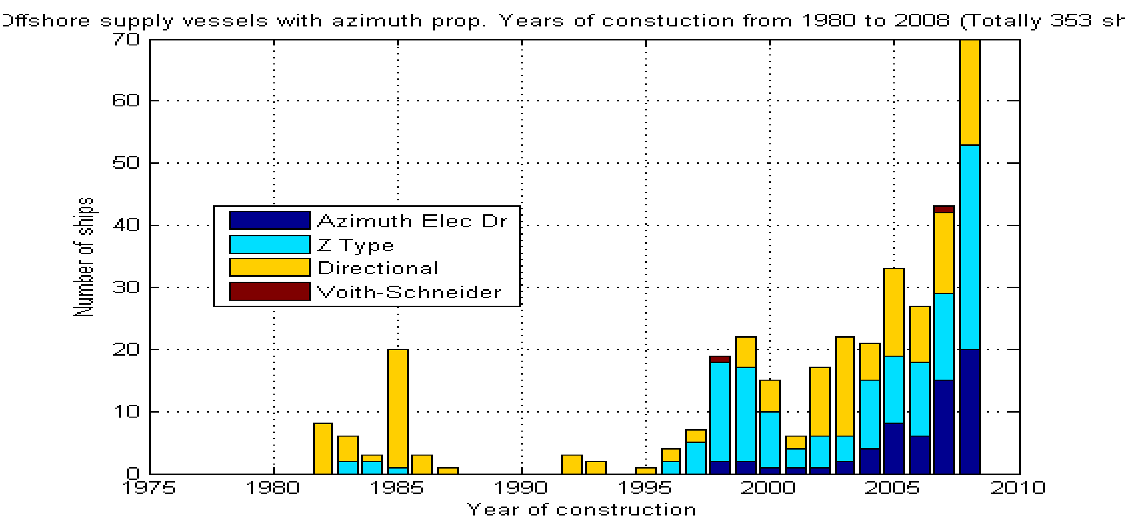




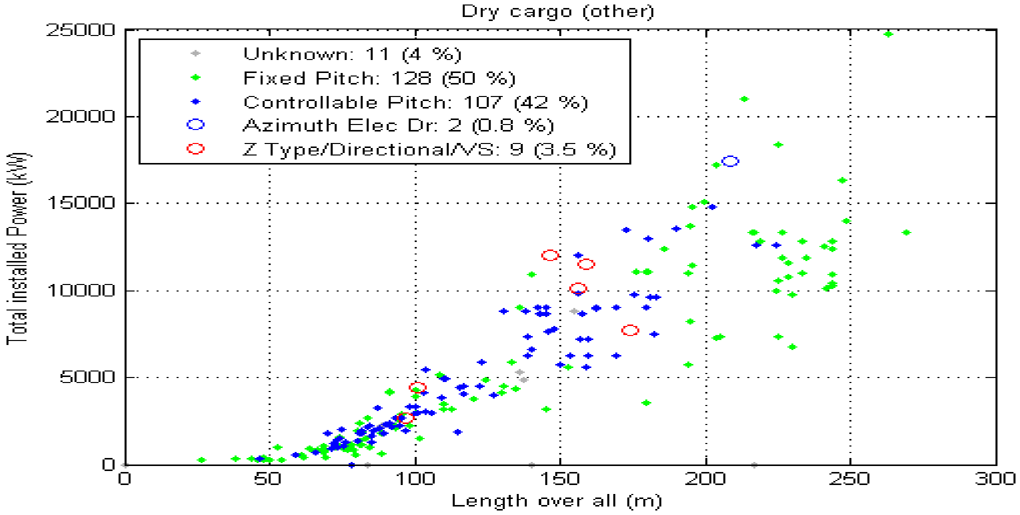
12 OFFSHORE - SUPPLY VESSELS

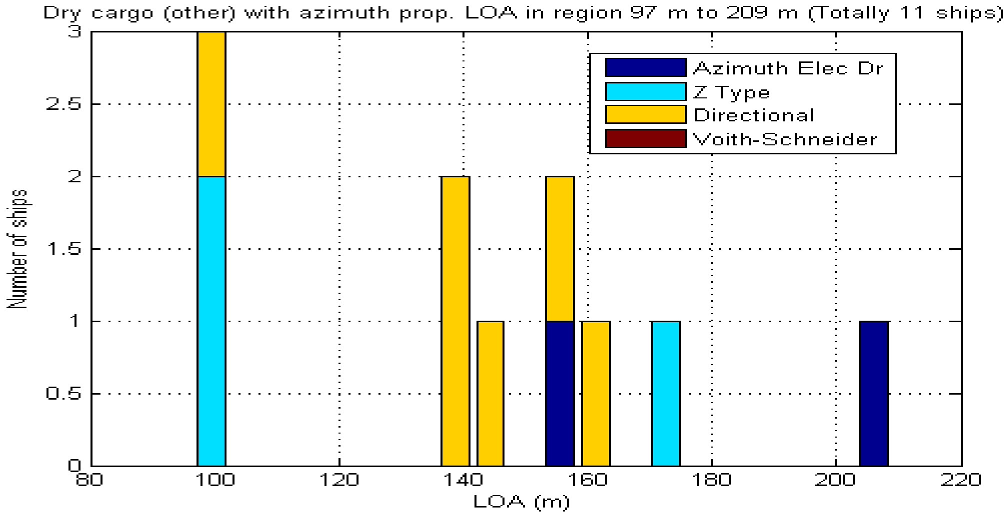


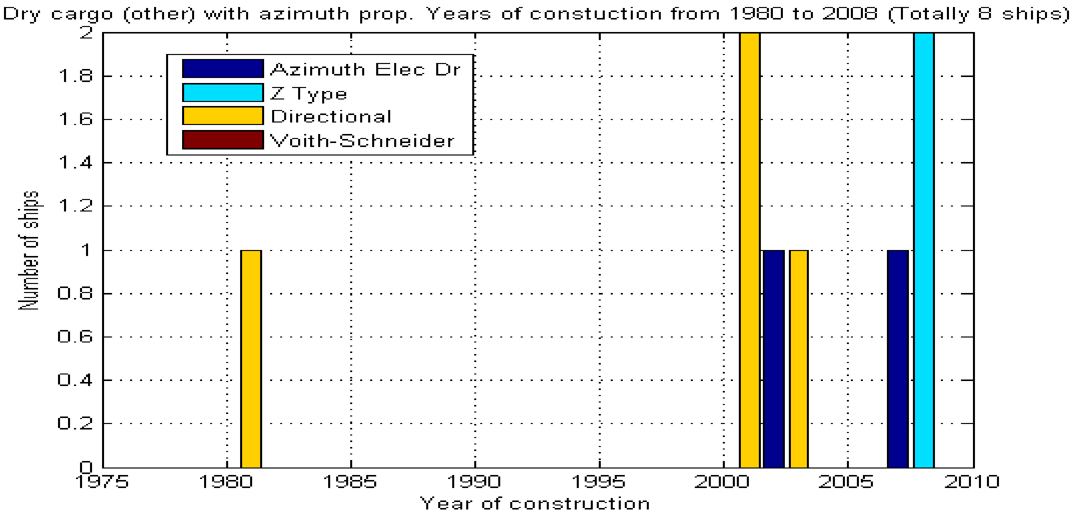




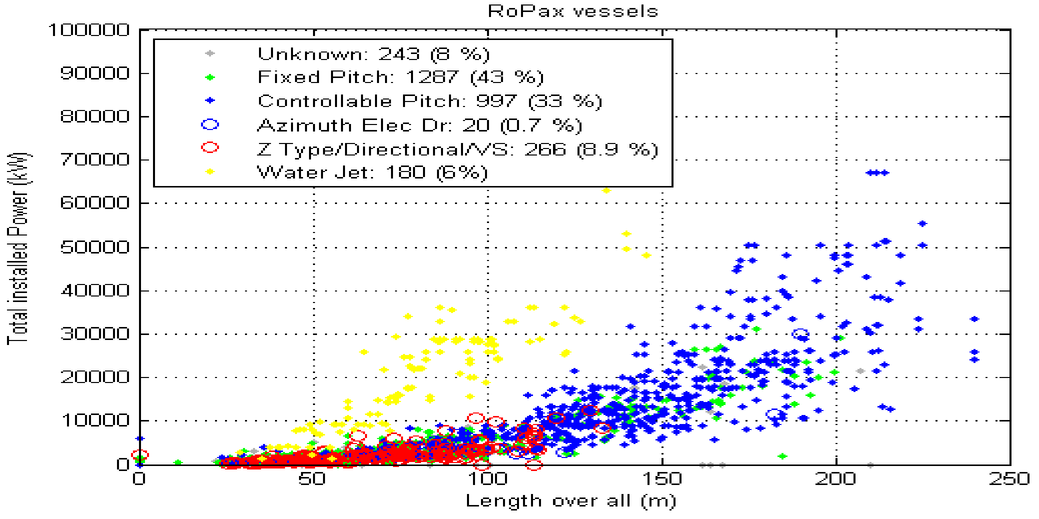
13 DRY CARGO - OTHER

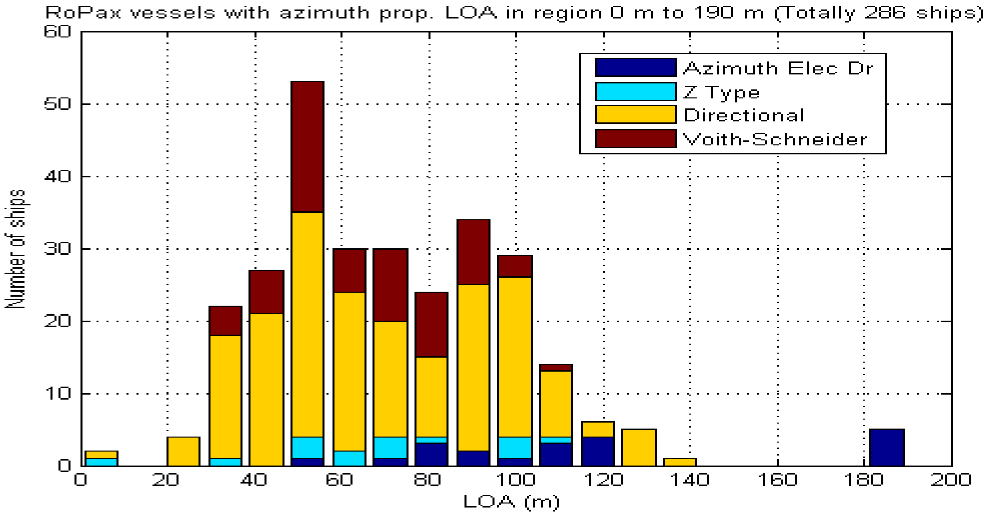


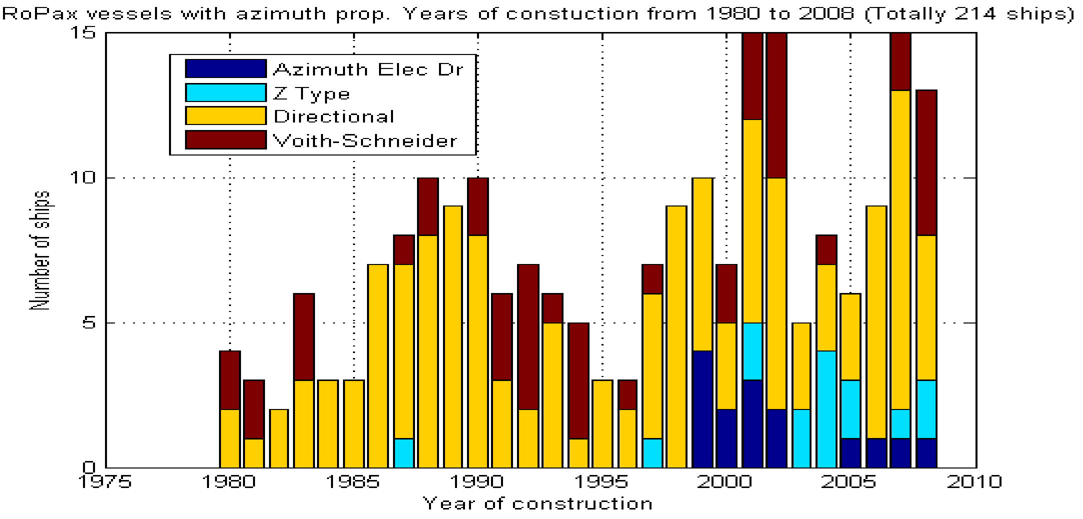




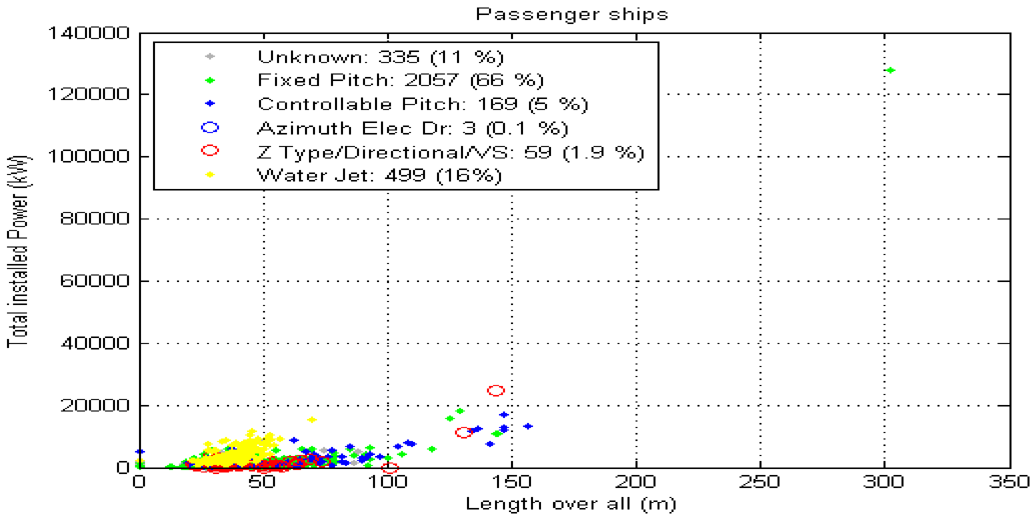
14 ROPAX VESSELS

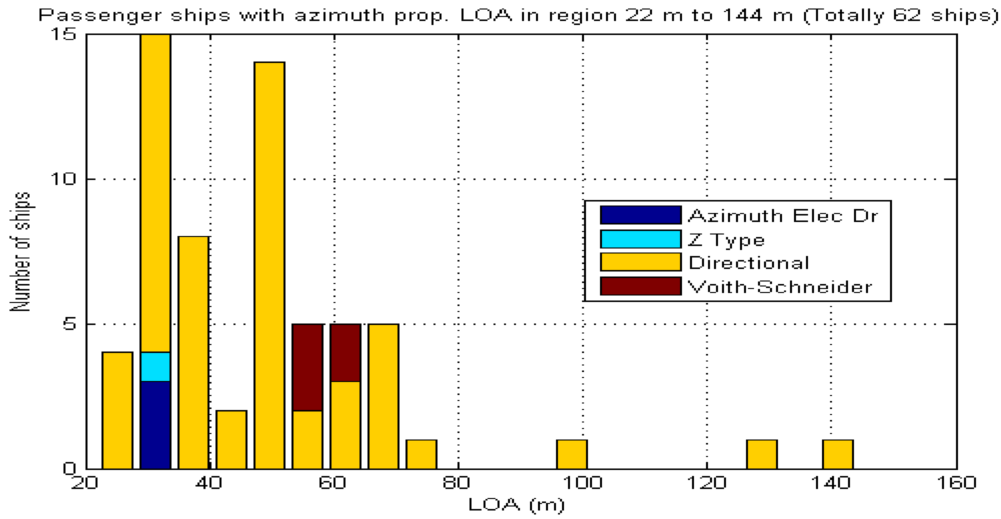


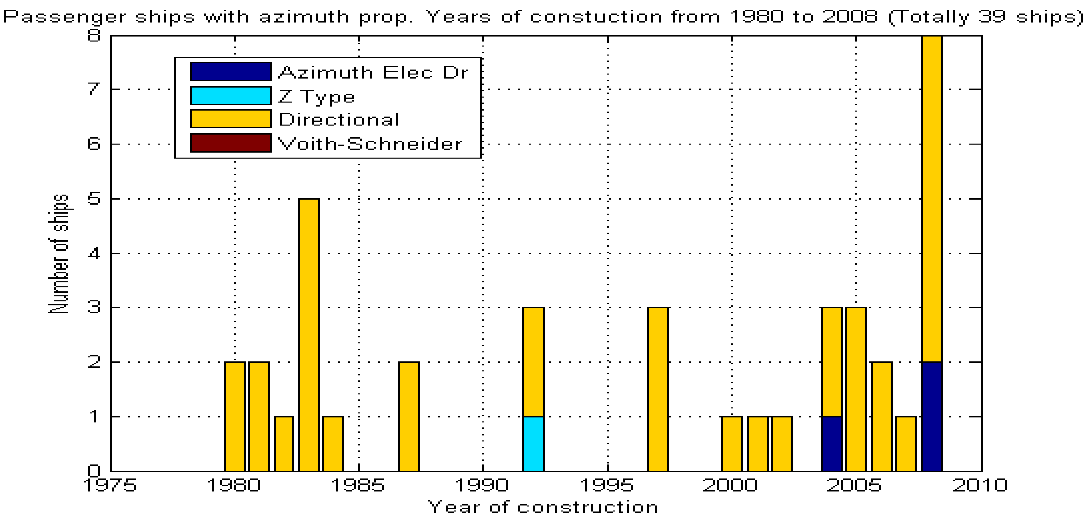




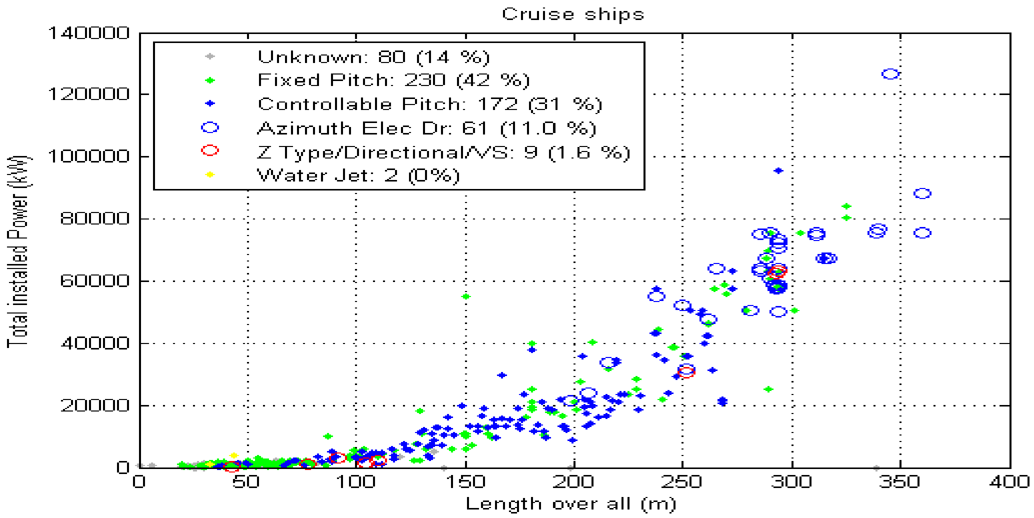
15 PASSENGER SHIPS

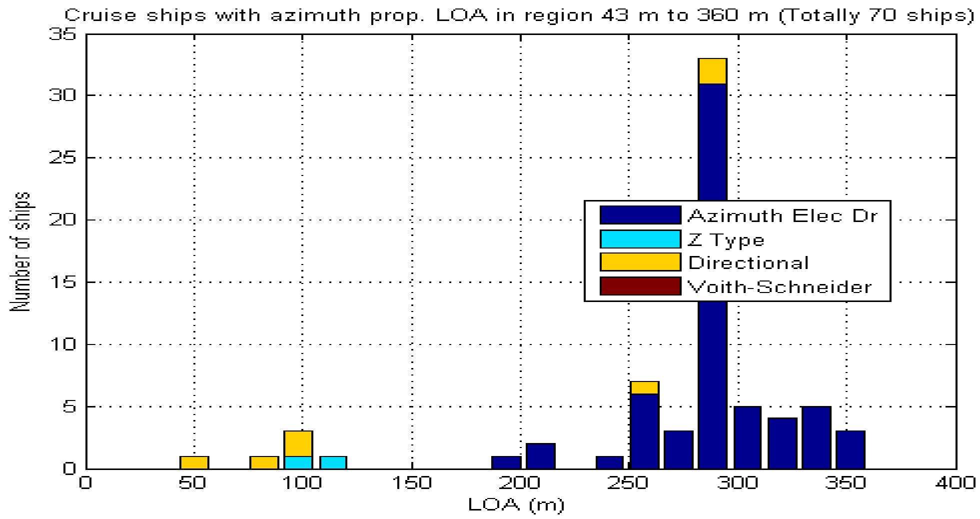


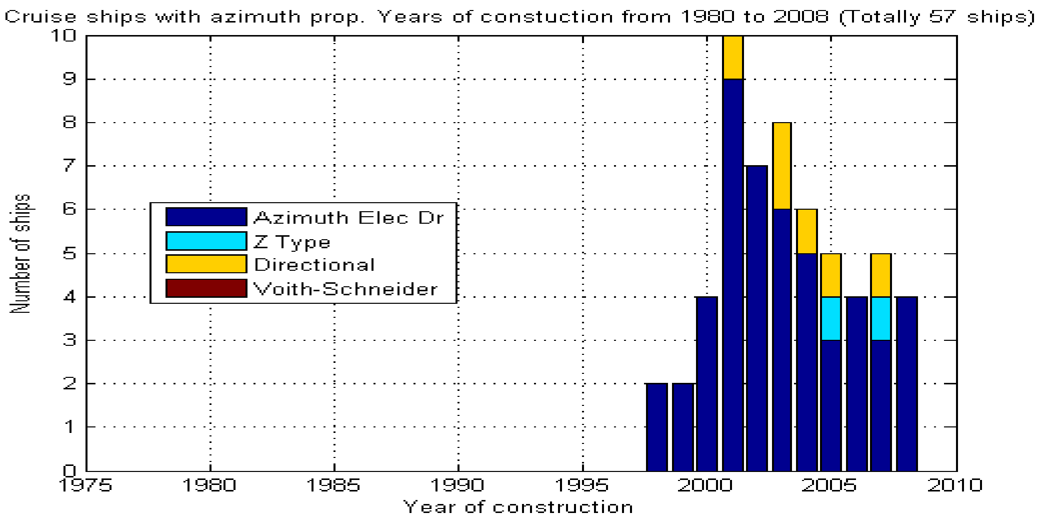




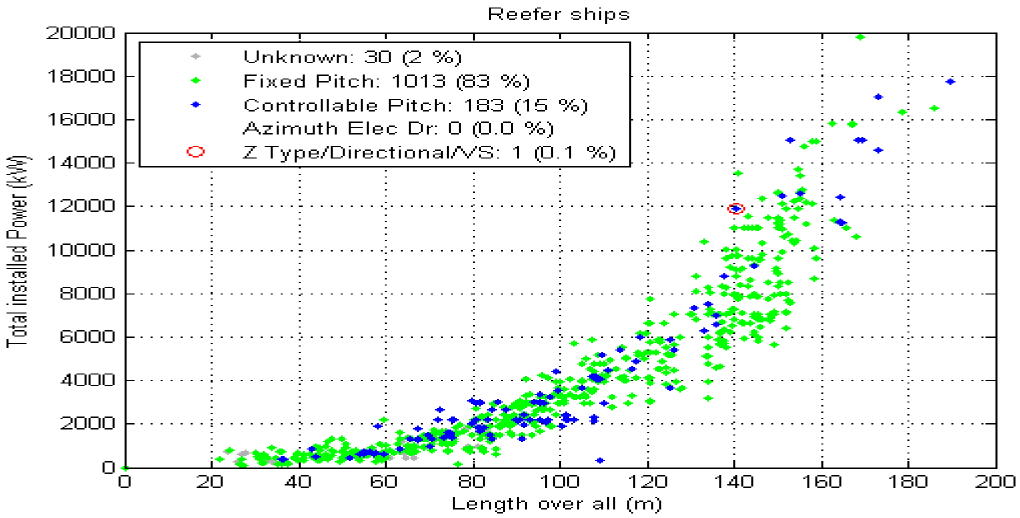
16 CRUISE SHIPS

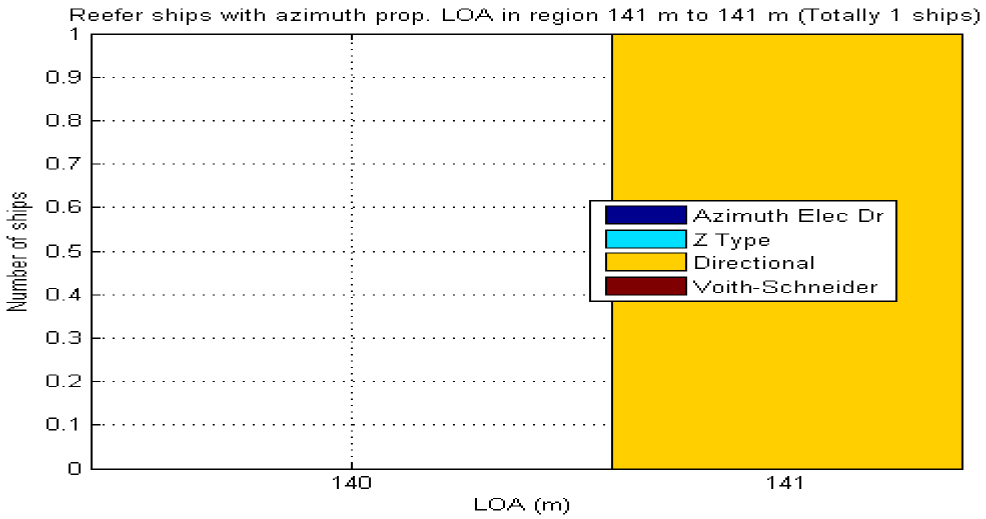


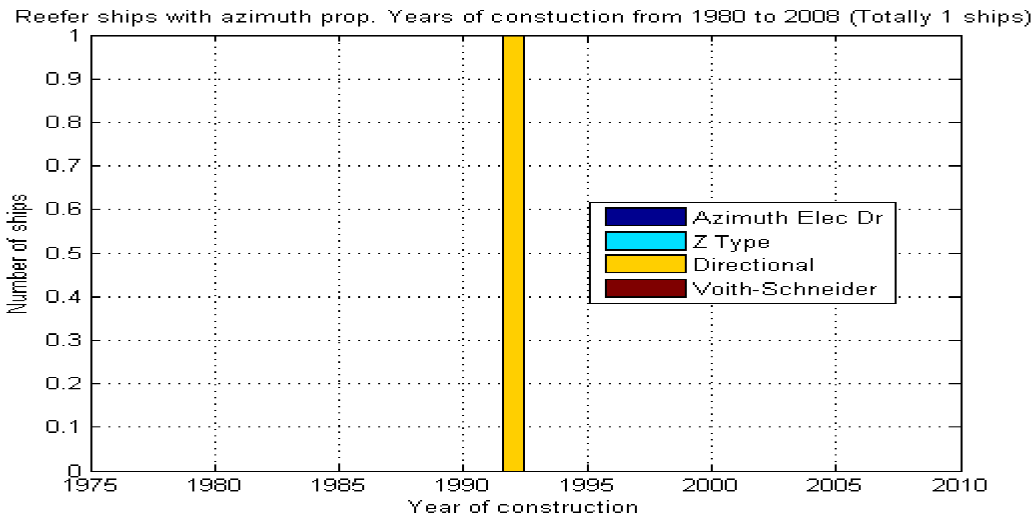




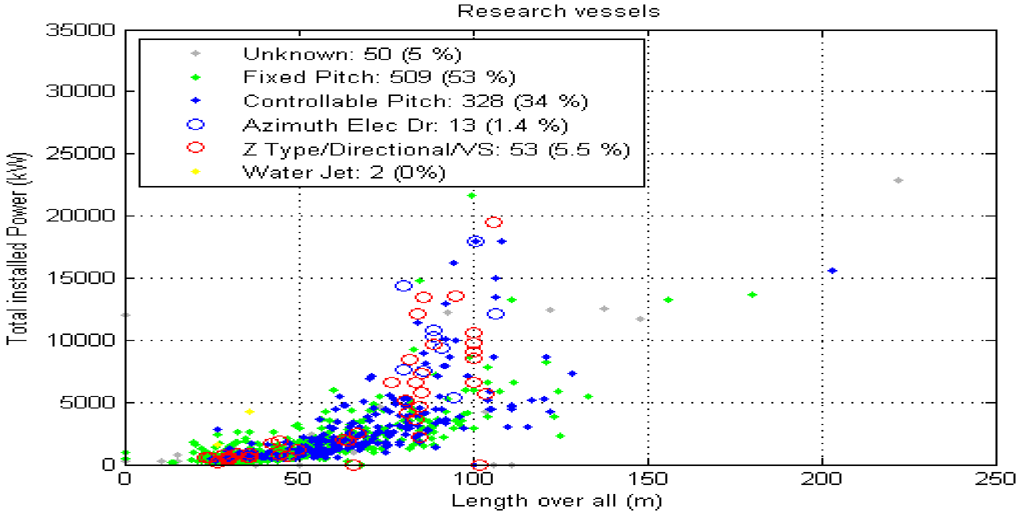
17 REEFER SHIP

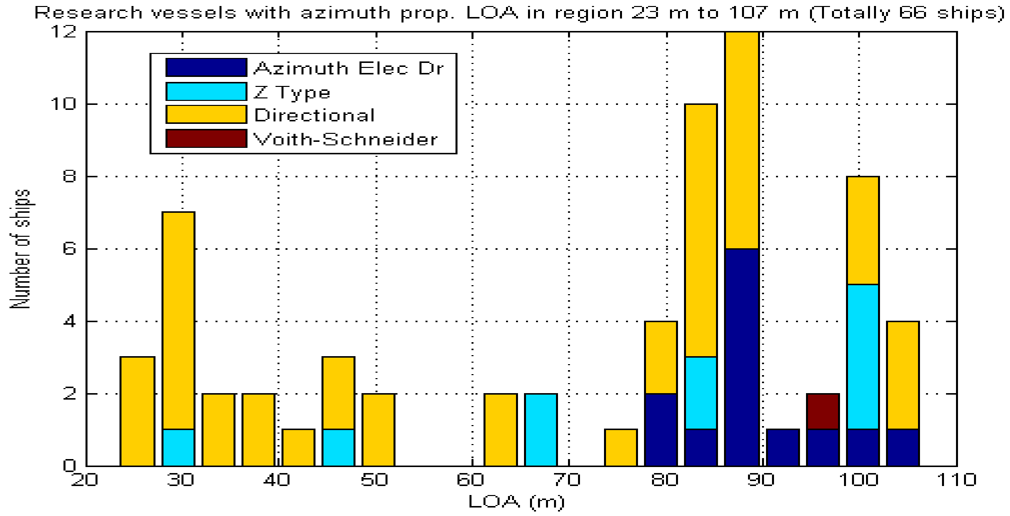


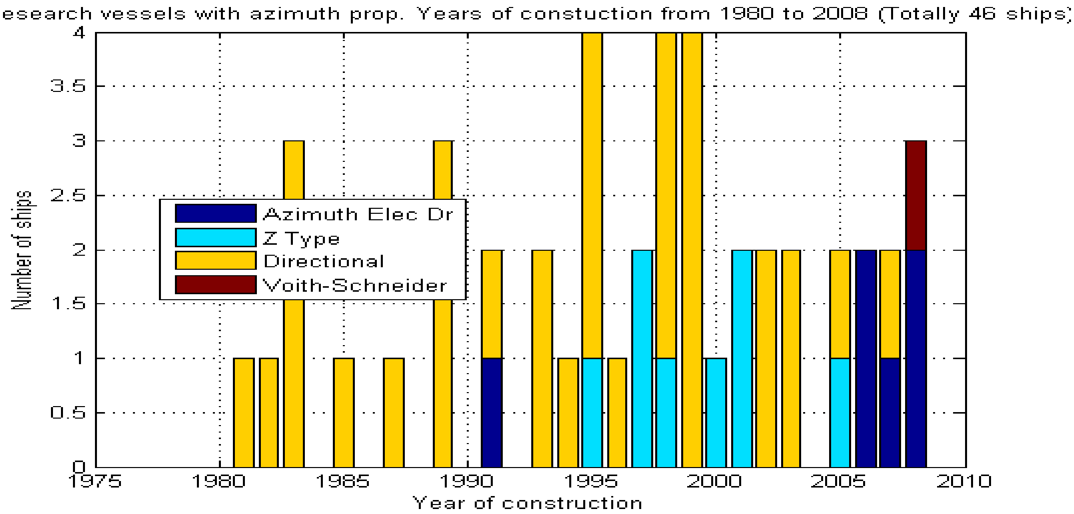




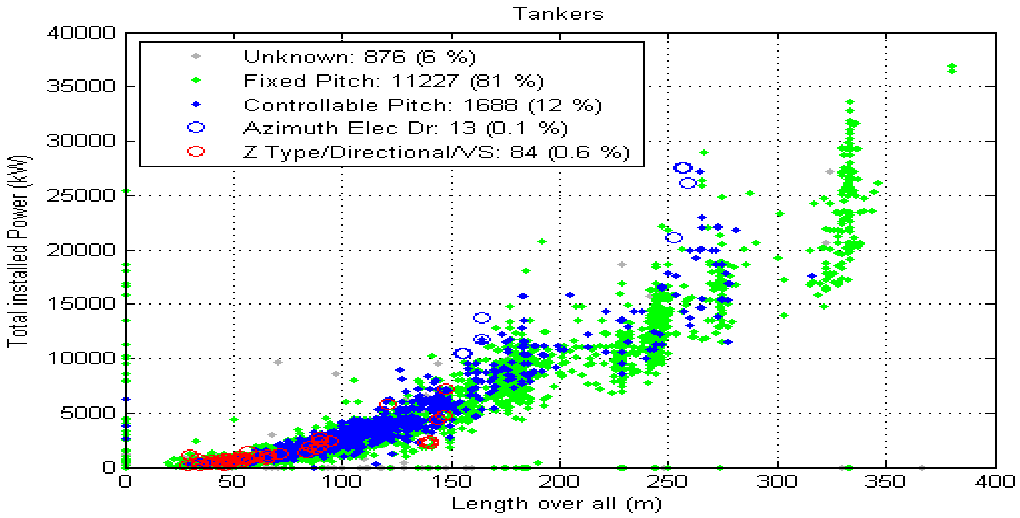
18 RESEARCH VESSELS

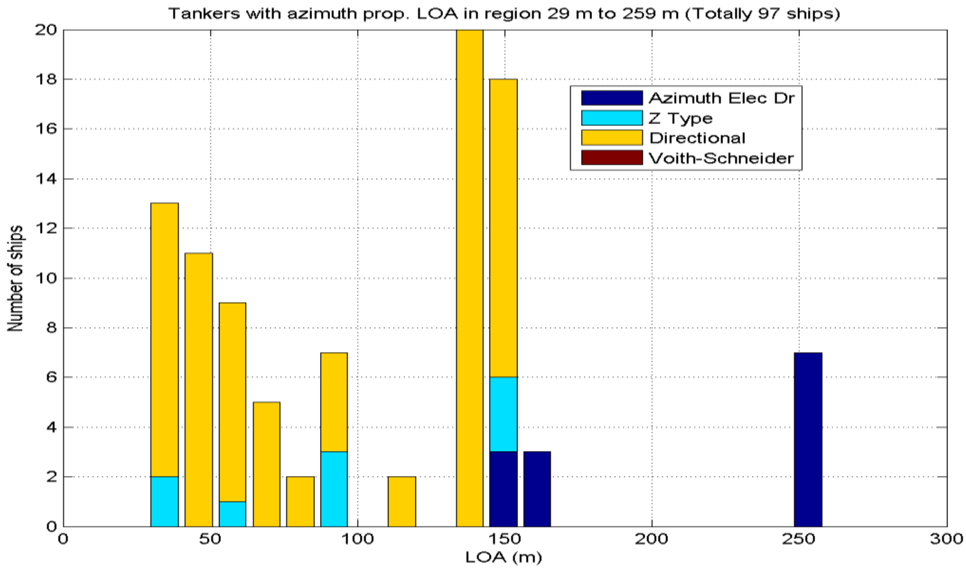


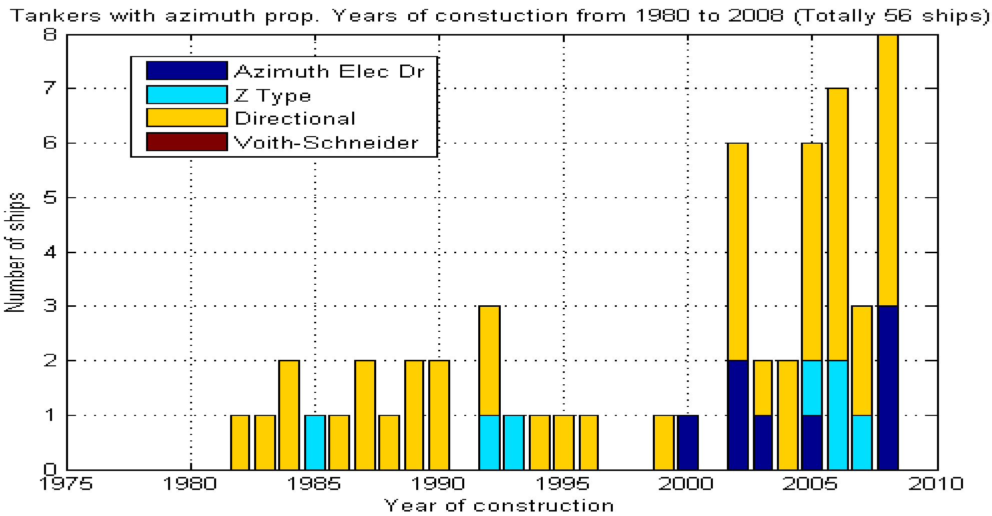




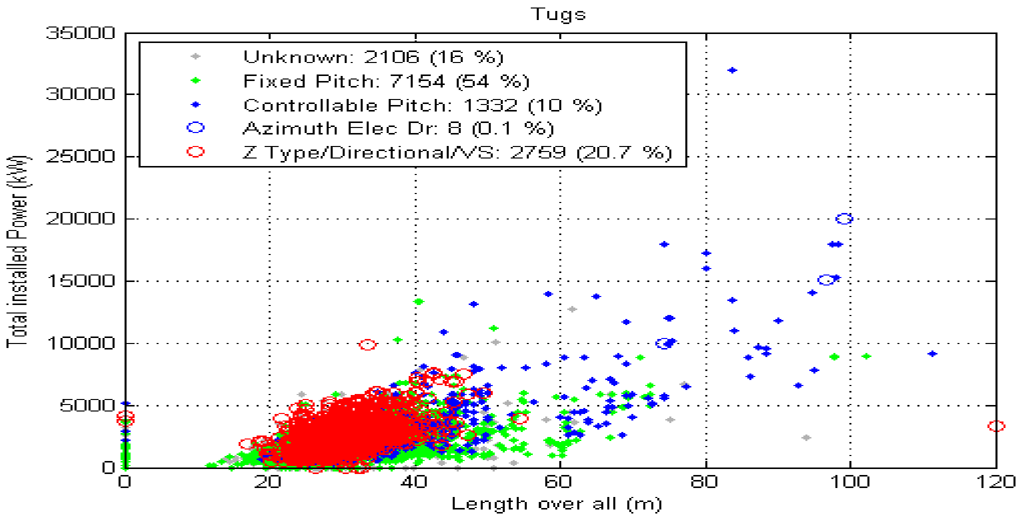
19 TANKERS

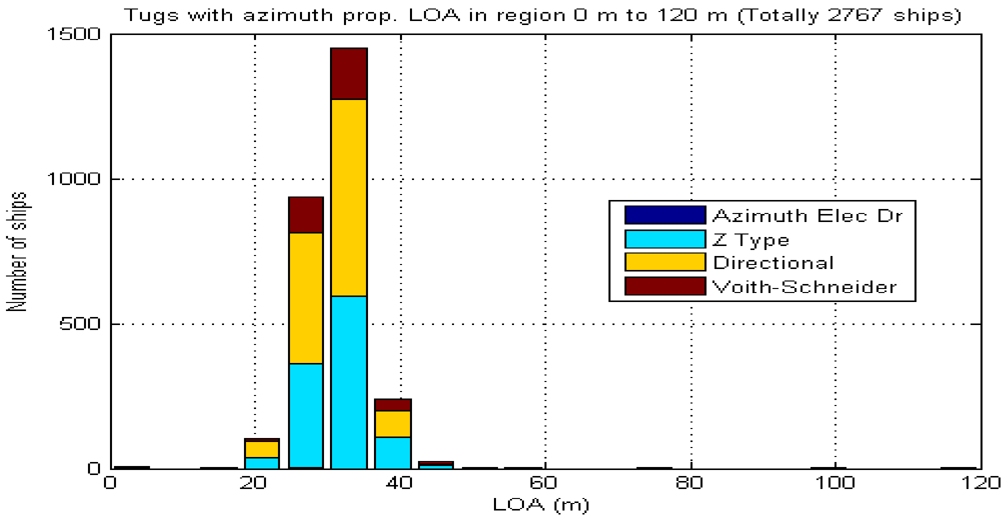

Tankers
Unknown: 876 (6 %)
Fixed Pitch: 11227 (81 %)
Controllable Pitch: 1688 (12 %)
Azimuth Elec Dr: 13 (0.1 %)
Z Type/Directional/VS: 84 (0.6 %)
Total installed Power (kW)
Length over all (m)

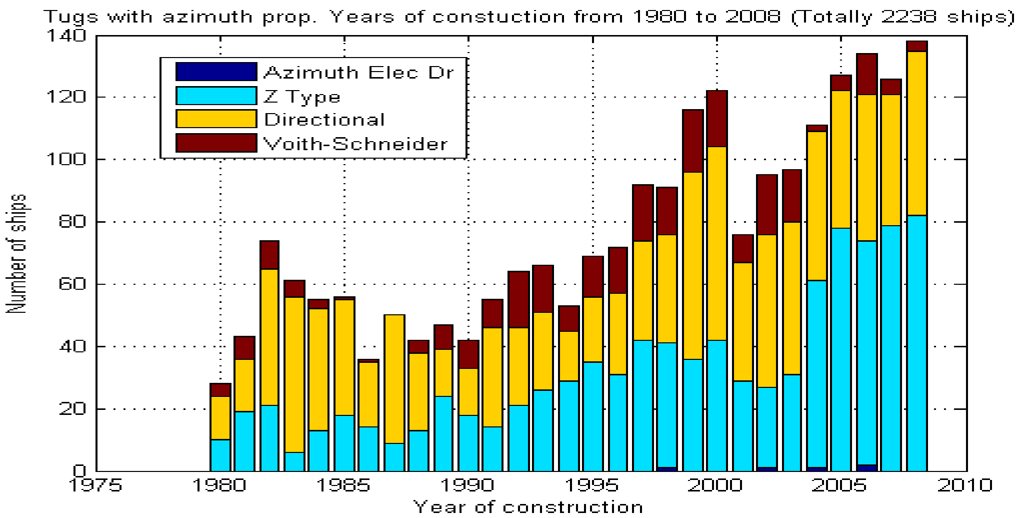

Tankers with azimuth prop. LOA in region 29 m to 259 m (Totally 97 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
LOA (m)


Tankers with azimuth prop. Years of constuction from 1980 to 2008 (Totally 56 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
Year of construction

20 TUGS


Tugs
Unknown: 2106 (16 %)
Fixed Pitch: 7154 (54 %)
Controllable Pitch: 1332 (10 %)
Azimuth Elec Dr: 8 (0.1 %)
Z Type/Directional/VS: 2759 (20.7 %)
Total installed Power (kW)
Length over all (m)


Tugs with azimuth prop. LOA in region 0 m to 120 m (Totally 2767 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
LOA (m)


Tugs with azimuth prop. Years of constuction from 1980 to 2008 (Totally 2238 ships)
Azimuth Elec Dr
Z Type
Directional
Voith-Schneider
Number of ships
Year of construction

Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title:

Deliverable 1.1:

Survey of existing conference series and published knowledge

List of paper titles

Introduction

The aim of this task is to review existing hydrodynamic knowledge with respect to the ability to model azimuthing control devices. The objective is to survey available and ongoing sources of information and in doing so to compile a database of existing capabilities. The main areas of focus will include:

- Determination of basic groups of interest.
- Survey of past projects outcomes and recommendations.
- Survey of existing conference series and published knowledge.
- Explore output from ongoing related initiatives and workshops.
- Discuss output from pilot associations and operators forums.
- Compile list of subject specific terminology and definitions.

Specifically, this task report deals with the third item on the list by survey existing conference series and published knowledge.

Papers are reviewed and summarised in the following tables. The full reference is included together with a summarised abstract. Key words are identified and use to generate a reference index at the end of the document.

Reference at a glance

To aid the quick identification of papers of interest, the 'reference at a glance' icons are introduced. Four key subject areas are chosen which it is hoped best represent the specific interests of likely readers. The subject icons that best represent the content of the paper in question are highlighted in the right of the respective table; with definition provided in the table below.

Manoeuvring prediction; including control and motion response.

Propulsive performance and modelling; including cavitation testing.

Operational and Human factors; including general arrangements.

Marine engineering; including electric motor technology and ship structure.

Main reference sources

T-POD	First International Conference on Technological Advances in Podded Propulsion, Newcastle University, Newcastle-upon-Tyne, United Kingdom, 2004.
T-POD'06	Second International Conference on Technological Advances in Podded Propulsion, L'Aber Wrac'h, France, 2006.
MARSIM'03	International Conference on Marine Simulation and Ship Manoeuvrability, Kanazawa, Japan, 2003.
MARSIM'06	International Conference on Marine Simulation and Ship Manoeuvrability, Treshiling, Netherlands, 2006.
MARSIM'09	International Conference on Marine Simulation and Ship Manoeuvrability, Panama City, Panama, 2009.

Also included: various conference and journal articles.

1 Sea trial experience of the first passenger cruiser with podded propulsors

Author(s)	Kurimo, R.
Pages	743 to 748
Year	1998
In	Practical Design of Ships and Mobile Units - PRADS'98
City	Hague, the Netherlands
Publisher	Elsevier
Key words	sea-trials, manoeuvring criteria, validation
Synopsys	The paper describes the propulsive performance and manoeuvring characteristics of a cruse ship with pods; during the sea-trials (some comparison is made with model test data). Also, the performance is compared with non-pod-driven sister ships. Discussion is made regarding the applicability of manoeuvring criteria for pod-driven ships.

2 Manouevring aspects of fast ship with pods

Author(s)	Toxopeus, S., Loeff, G.
Pages	392 to 406
Year	2002
In	3rd Int. Euro Conf. on High-Performance Marine Vehicles
City	Bergen, Norway
Publisher	Bertram, V., (also see: WEGEMT)
Key words	design guidelines, course-stability,
Synopsys	The paper describes the aspects of application of pods from a manoeuvring viewpoint, compared to ships with conventional propulsion; highlighting the benefits and points for attention. Design guidelines to improve the manoeuvring performance are given and operational issues are discussed.

3 An investigation into the course-stability and control of a fast, pod-driven Ropax

Author(s)	Woodward, M. D., Clarke, D., Atlar, M.
Pages	437 to 447
Year	2002
In	3rd Int. Euro Conf. on High-Performance Marine Vehicles
City	Bergen, Norway
Publisher	Bertram, V., (also see: WEGEMT)
Key words	semi-empirical tools, derivative prediction
Synopsys	The paper describes work conducted in the OPTIPOD project (EU funded project under FP5); using a fast Ropax as case-study. Semi-empirical tools for predicting the manoeuvring derivatives of hull-forms that have been modified for pods are presented. Validation is made by comparison with captive and free-running model tests; using the case-study Ropax.

4 Parametric investigations designed to help focus pod technology developments

Author(s)	Goubault, P., & Pérrée, J.
Pages	27-38
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	parametric, optimisation, performance
Synopsys	As part of the FASTPOD project, the paper looks into parametric optimization of pods dimensions. Investigations focus on the aspect-ratio of the electric motor and the impact on both motor efficiency and hydrodynamic performance. The paper concludes that the best approach is to optimise the motor reliability at the expense of hydrodynamic performance; finding body dia. of 50% of the propeller dia. to be acceptable.

5 Hull design and optimisation with pod propellers with 5 and 6 blades

Author(s)	Bertaglia, G., Lavini, G., Scarpa, S.,
Pages	39-58
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	Propeller diameter, stern-lines
Synopsys	The paper investigates the effects of larger propeller diameter to achieve higher service flexibility demanded by Panama cruise ships. The effects of higher power and thus induced pressure on optimal stern-lines are considered. Conclusions find that higher number of blades is preferable; confirmed by model testing. Lower dia. and mean-pitch with high rpm and clearance seems to be a better compromise.

6 New podded drives for the power range of 1-5 MW

Author(s)	Kaul, S.,
Pages	61-72
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	lower-power, bevel-gear
Synopsys	The paper presents new electric propusors for lower power ranges; introducing an innovation through the use of cooling through a hollow propeller shaft. Presented as an intermediate solution between pod and mechanical rudder, a bevel gear reduces the motor speed down to propeller speed. Conclusion present various design attractions including better possibilities for space arrangements in the engine room.

7 Rim-driven propulsion- Improving reliability and maintainability over today's pods

Author(s)	Blarcom, van B., Franco, A.I., Lea, M., Peil, S., Dine, van P.
Pages	73-88
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	rim-drive, nozzle
Synopsys	The paper presents an innovation known as the Rim-driven pod; wherein the rotor is situated in a ring at the propeller tips and the stator is situated in a nozzle like duct surrounding the propeller. The paper focuses on features that support reliability and maintenance. Conclusions find features attractive but await full-scale dater for validation.

8 Pod propulsion research and development at ARL-Penn State

Author(s)	Eaton, J. E., Billet, M. L.
Pages	89-106
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	design-code, RANS
Synopsys	The paper outlines research capabilities, facilities and proprietary design code at the title institution. The paper outlines efforts applied to non-conventional propulsors such as pods, water-jets and the Rim-driven pod concept. Design methods for RDP are discussed including the application of asymmetric RANS codes to assess/analyse the motor gap flow field.

9 Operability of fast podded Ropax ships in rough seas

Author(s)	Sariöz, K., Atlar, M., Sariöz, E., Woodward, M. D., Sampson, R.
Pages	109-124
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	motion-response, seakeeping
Synopsys	The paper reports on a comparative study of motion response of a conventional and a pod-driven Ropax; operating in a North sea environment. The evaluation is made using a 'Seakeeping Performance Index' and an 'Average Attainable Speed'. The main conclusions find that, despite having 20% less displacement, the pod-driven configuration has better seakeeping. Also, that pod arrangements may improve vertical motions.

10 Effects of pods on the roll behaviour of passenger vessels

Author(s)	Turan, O., Tuzcu, C., Clelland, D., Ayaz, Z.
Pages	125-134
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	roll, damping
Synopsys	The paper presents an experimental study on the effects of pod structure on roll damping and roll motion; considering both 3D pods and a 2D approximation (thin plates). The concussions find an effect of pods on damping and roll motion. It is found that reduction in motion due to 3D pods is not as large as with 2D pods; thus the approximation should be avoided.

11 Manoeuvring aspects of pod-driven ships

Author(s)	Ayaz, Z., Turan, O., Vassalos, D.
Pages	135-152
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	roll, optimisation
Synopsys	The paper presents a modified 6-dof manoeuvring model for pod-driven ships. The derived model is validated by comparison between simulated and experimental results of standard criteria manoeuvres. The conclusions suggest that dangerous roll conditions may be avoided through design optimisation. Also, the conclusions speculate that the first-overshoot criterion me be in question.

12 Full scale performance of double acting tankers "Tempera & Mastera"

Author(s)	Sasaki, N., Laapio, J., Fagerstrom, B., Juurmaa, K., Wilkman, G.
Pages	155-172
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	double-acting tanker, ice-breaking
Synopsys	The paper presents manoeuvring and resistance, prediction and trial results for two Double-Acting Tankers. The concept uses the bow for open sea performance and the stern as an ice-breaking bow; utilising an azimuthing pod to retain the correct propeller rotation for both conditions. The conclusions find that the various power prediction methods examined exhibited 3-4% deviation.

13 Double Acting Tankers: Experiences from model tests and sea trials

Author(s)	Trägårdh, P., Lindell, Per.,Sasaki, N.
Pages	173-186
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	double-acting tanker,
Synopsys	The paper presents a manoeuvring and resistance model test program for two Double-Acting Tankers (see above). The conclusions present a 6.3% improvement in propulsive performance. Also, the design of a fin on the pod body enables the design to meet the IMO manoeuvring criteria; whereas the unmodified design would not. Simulation study demonstrated reduced mooring line forces as a result of DP controlling bow-thruster and azimuthing pod.

14 Measuring podded propeller performance in ice

Author(s)	Akinturk, A., Jones, S. J., Rowell, B., Duffy, D.
Pages	187-198
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	ice, blade-loads
Synopsys	The paper describes preliminary results of experiments using a setup designed for measuring loads on pod propellers operating in ice. The system is able to measure load on the propeller shaft bearings and blade loads. The results suggest that the bearings undergo cyclic loading during ice encounters. The conclusion suggest that propeller induced side-forces may be important for manoeuvring and course-stability.

15 On the hydrodynamic design of podded propulsion for fast commercial vessels

Author(s)	Sánchez-Caja, A., Pylkkänen, J. V.
Pages	201-210
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	non-symmetric strut, RANS
Synopsys	The paper deals with the optimisation of the pod body using RANS solver FINFLO for two high speed (35-38 knots) vessels; a Ropax and a Cargo ship. A non-symmetric strut is designed in order to delay cavitation inception. Conclusion find the analysis too is suitable for design with the right choice of grid. Also, for high speed the design of the propeller with the pod housing is critical due to danger of cavitation on both propeller and strut.

16 Numerical simulations of flows around a ship with podded propulsor

Author(s)	Ohashi, K., Hino, T.
Pages	211-222
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	Navier-Stokes, contra-rotating
Synopsys	The paper describes the application of a Navier-Stokes solver with as unstructured grid method for the performance prediction of a ship with pods. Podded propellers in contra-rotating configuration are compared with measured results. Pusher and puller type pod arrangements are investigated. Conclusions suggest that, although accuracy improvements are needed, the information provided from computed flow-fields are useful for ship hull design.

17 On a propulsion prediction procedure for ships with podded propulsiors using RANS-code analysis

Author(s)	Chicherin, I.A., Lobatchev, M.P., Pustoshny, A.V., Sánchez-Caja, A.,
Pages	223-236
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	pod-housing, RANS
Synopsys	The paper presents an analysis made with RANS code for the pod-housing at model and full scale. Conclusions suggest that it is not possible to scale the pod-housing drag with the 0.5 scaling coefficient; conventionally applied to appendages. It suggests that the form-factor concept is inapplicable to housing drag scaling because the form-factor is a function of propeller loading and Reynolds number.

18 Fluctuating pressure distribution on pod

Author(s)	Deniset, F., Jaouen, R., Billard, J-Y., Laurens, J-M.
Pages	237-244
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	potential code, RANS
Synopsys	The paper presents a method based on coupling between a potential flow code and a RANS flow solver; used to perform unsteady flow simulations around the pod and propeller. Steady and unsteady computations are performed and obtained velocities imposed as inlet boundary conditions. Focusing on the grid, the fluctuating pressure distributions on the strut and nacelle are analysed to estimate risk of cavitation, vibration and fatigue.

19 On the design of a shafted propeller plus electric thrusters contra-rotating propulsion complex

Author(s)	Bushkovsky, V. A., Frolova, I. G., Kaprantsev, S. V., Pustoshny, A. V., Vasiljev, A. V., Jakovlev, A.J., Veikonheimo, T.
Pages	247-260
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	contra-rotating, fast ships
Synopsys	The paper discusses problems associated with the design of contra-rotating propellers consisting of a conventional shaft in combination with a pod. Conclusions find advantages for large and fast ships. It suggests that accurate propeller design is possible by combining software with tests to determine the propeller couple with pod housing. Suggested crucial to avoid interaction of fore propeller hub and aft blade cavitation when steering with pod.

20 Calculation methods for the steering forces of a pod in hybrid propulsion

Author(s)	Ruponen, P., Matusiak, J.
Pages	263-276
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	contra-rotating , steering forces
Synopsys	The paper considers a prediction method for estimating steering forces for a conventional propeller and pod in contra-rotating configuration. Required inputs are open-water characteristics for both propellers and simplified geometry for the pod. The method is developed for the 1st quadrant of the pod propeller and for steering smaller than the stall angle. The paper concludes that sufficient accuracy is obtained for simplified manoeuvring simulation and for a first estimate of force.

21 Propulsive performance of a contra-rotating podded propulsor

Author(s)	Ukon, Y., Ohashi, K., Fujisawa, J., Hasegawa, J.
Pages	289-303
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	contra-rotating pod, dynamometer
Synopsys	The paper presents the propulsive performance experimental investigation of a contra-rotating pod; two propellers on one end of the pod. A dynamometer is manufactured for open-water and self-propulsion tests. The paper concludes that the configuration shows promise and that the 7-component balance worked.

22 Study on the powering performance evaluation for the CRP-pod propoulsion ships

Author(s)	Go, S., Seo, H., Chang, B. J.
Pages	277-287
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	contra-rotating , RPM
Synopsys	The paper considers performance prediction for contra-rotating propeller configurations; using as case study a system designed for a 10,000 TEU container ship. Consideration is made regarding the relationship between the RPM of two propellers. Conclusions state that the effects of speed on the powering ration at fixed RPM is small; thus design speed is valid for neighbouring speeds.

23 Investigations about the forces and moments at podded drives

Author(s)	Heinke, H-J.
Pages	305-319
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	steering forces, dynamometer, crash-stop
Synopsys	The paper presents model tests with 4- and 5-bladed propellers in both push- and pull-configurations; together with the development of a 6-component dynamometer. Hub, propeller and housing geometry are investigated. Tests include forces and moment coefficients at different steering angles and crash-stop manoeuvres. Differences are identified in steering forces for pusher and puller types. Effect of cavitation is found to be small.

24 Preliminary results of testing on the dynamics of an azimuting podded propulsor relating to vehicle manoeuvring

Author(s)	Stettler, J. W., Hover, F. S., Triantafyllou, M. S.
Pages	321-337
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	dynamic forces, PIV
Synopsys	The paper presents experimental results on the forces acting on a pod subjected to nonlinear manoeuvring dynamics. Wake flow visualisation is achieved using PIV. Contour plots for steering angles up to ±45° are argued to be nearly linear in range of typical design advance coefficient. Conclusions suggest possibility of linearization and decoupling of surge-sway-yaw.

25 Comparison of stopping modes for pod-driven ships

Author(s)	Woodward, M. D., Atlar, M., Clarke, D.
Pages	339-354
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	propeller added-mass, crash-stop, simulation
Synopsys	A continuous function is derived, describing the hydrodynamic forces on both the propeller and pod-body, for any load condition and helm-angle; including fluid-damping and added-mass effects. Simulations of 4 different stopping manoeuvres are performed. The paper concludes that a pod can stop a ship more rapidly and with more control than with a conventional arrangement.

26 Open water experements with two pod propulsion models

Author(s)	Grygorowicz, M., Szantyr, J. A.
Pages	357-370
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	manned-model, single- and twin-pod version
Synopsys	The paper presents open-water tests on a large manned-model; with a twin and single pod configuration. Conclusions find that for both configurations the axial and transverse forces depend strongly on drift angle. For both versions the transverse force showed a complicated dependence on propeller loading and on external velocities. Conclusion indicates that the single pod version may prove difficult in operation but unfavourable effects should cancel for twin arrangement.

27 Manoeuvring tests of a vessel with pod propulsion

Author(s)	Kobylinski, L.
Pages	371-381
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	manned-model, course-stability, steering
Synopsys	The paper presents manoeuverability and ship-handeling tests for a single- and twin-pod manned-model. Directional stability was found to unsatifactory, even with large fins attached; with the single-pod version fairing worst. Steering trials in a narrow channel confirmd findings; with the single-pod version proving difficult or even imposible to keep within the fairway.

28 Selected aspects of pod propulsor work in operational conditions

Author(s)	Kanar, J
Pages	N/A
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	
Synopsys	NB: Only the abstract appears in the conference proceedings (suggest contacting author: CTO Ship Design and Research Centre, Poland).

29 Cavitation and vibration investigations for podded drives

Author(s)	Friesch, J.
Pages	287-399
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	cavitation, vibration, noise
Synopsys	Specific problems related to increased ship speed are addressed and cavitation tests with moving pod discussed. Cavitation tests for both propeller and pod-housing are conducted and correlations to full-scale drawn. Wake-field for twin-pods proved very smooth offering low excitation, vibrations and noise. Conclusion suggests that, for high speeds, larger number of blades is preferable.

30 Podded rudder

Author(s)	Junglewitz, A., el Moctar, O., Franič, S.
Pages	401-418
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	double-ended-pods, RANS
Synopsys	The paper considers steering forces for double-ended-pods compared to conventional rudders; based on RANS code analysis. Conclusions indicate that there is little difference in steering forces at design speed but at lower speed the pod has the advantage compared to the rudder. It is claimed that an estimation of the side force based on simple formula contained in the Classification Rules is possible.

31 Numerical model for naval pod

Author(s)	Sigrist, J-F., Gervot. C., Lainé, C., Le Bert, J-F., Barbarin, R.
Pages	419-429
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	vibro-acoustic simulations, electric motor
Synopsys	The paper presents vibro-acoustic simulations used to evaluate the concept of an electric motor elastically mounted into the housing. Results indicate low noise levels; concluded to be due to the permanent magnet motor. The developed numerical model is argued to be sufficiently reliable for mechanical calculations.

32 Experience of Festival Cruises operating pod driven ships

Author(s)	Kontes, T. C., Kontes, C. T.
Pages	431-443
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	seals, bearings, failures
Synopsys	The paper describes technical failures (mechanical and electrical) encountered over a 3-yer operating period. Measures used to resolve such problems are described and evaluated. Conclusions find that the most critical issues are associated with the seals and bearings; corrective measures being successful. In addition good monitoring techniques are said to be essential.

33 Design of a model pod test unit

Author(s)	MacNeill, A., Taylor, R., Molloy, S., Bose, N., Veitch, B., Randell, T., Liu, P.
Pages	447-457
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	pod-dynamometer, towing-tank, gap-pressure
Synopsys	The paper describes the design of a pod dynamometer to be used in conjunction with a towing-tank. The unit has the capability to measure: total unit thrust; propeller thrust and torque at the hub; thrust at the end of the propeller shaft; pod shell drag; shaft speed. The unit also has the facility to measure the local pressure in the gap between the propeller-hub and the pod body; using 5 pressure gauges.

34 Systematic geometric variation of podded propulsion models

Author(s)	Molloy, S., Bose, N., Veitch, B., Taylor, R., MacNeill, A.
Pages	459-464
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	systematic series, propulsive efficiency
Synopsys	The paper describes the development of a systematic series (16 models), by multifactor analysis, used to qualify the propulsive efficiency of the pod configuration. Methods of drag testing are disused; no test data is presented.

35 Numerical and experemental investigation tools for preliminary design of podded propulsion components

Author(s)	Di Felice, F., Felli, M., Greco, L., Pereira, F., Salvatore, F., Testa, C.
Pages	465-481
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	LDA, PIV, RANS, hydro-acoustic, fluid-structure interaction
Synopsys	The paper presents experimental and theoretical techniques for the hydrodynamic and hydro-acoustic analysis of conventional and multi-component propulsion. LDA and PIV are compared with theoretical predictions base on boundary element methods for the propeller in invicid flow. The solver is said to include trailing vorticity analysis, sheet cavitation prediction and viscous flow correction. Radiated noise is evaluate by using either Bernoulli equation or Ffowcs-Williams and Hawkings hydro-acoustic model.

36 Experimental investigation of flow fileds around a podded propulsor using LDA

Author(s)	Wang, D., Atlar, M., Glover, E. J., Paterson, I.
Pages	483-498
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	LDA, wash, pod-hull interaction
Synopsys	The paper presents results of an experimental investigation into the velocity field of a pod, using LDA. Results are used to assess propeller wash and the interaction between the pod and the hull.

37 On the propulsive performance of a small bulk-carrier model with twin-podded propellers

Author(s)	Nakatake, K., Ando, J., Yoshitake, A., Sato, Y., Tamashima, M.
Pages	501-512
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	propulsive efficiency, scaling
Synopsys	The paper presents the testing of a bulk-carrier model with twin pods; mounted on dynamometers. Results for propulsive performance are presented and compared with ITTC 1978 prediction model (virtual full-scale). The conclusion suggests that as results depend on the advance, Fn and Rn, then the pod system should be treated as an appendage.

38 Numerical investigation of propulsive characteristics of podded propellers

Author(s)	Islam, M., Taylor, R., Quinton, J., Veitch, B., Bose, N., Colbourne, B., Liu, P.
Pages	513-525
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	hub-taper, propulsive efficiency
Synopsys	The paper presents a numerical investigation into the effects of hub-taper angle. Pulling and pushing configurations are considered and the effect of the pod-strut on K_T and K_Q with hub-taper angles of 15 and 20 deg are examined. Conclusion clam that taper angle is influence on propulsive efficiency; with more pronounced effect when in a highly-loaded condition.

39 Research on hydrodynamic computation model of pod propulsion

Author(s)	Cheng, M., Zhengfang, Q., Chenjun, Y., Xu, Z., Du, D.
Pages	527-547
Year	2004
In	First Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2004)
City	Newcastle-upon-Tyne, United Kingdom
Publisher	Newcastle University
Key words	potential flow, trailing vortex
Synopsys	The paper presents a potential flow model, with trailing vortex, for prediction of the steady hydrodynamic performance of a pod; validated with experimental data. Conclusion claim that the introduction of the trailing vortex method shows improved prediction.

40 Balanced-Pod – The next generation in pod technology

Author(s)	Woodward, M. D., Atlar, M.
Pages	Session 1
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	Balanced-Pod, speed-loss
Synopsys	The paper presents a new configuration of pod, named as the Balanced-Pod. The paper presents both qualitative and quantitative arguments in support of the new design. Specifically, the study shows results for numerical evaluation argued to show that the Balanced-Pod experiences less speed-loss when compared to equivalent manoeuvres using a standard azimuthing pod arrangement.

41 Manoeuvrability of 749GT cement tanker with three different pod propulsion system

Author(s)	Kano, T., Kayano, J., Sakoda, M., Takekuma, K.
Pages	Session 1
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	hull-lines, course-stability, hybrid, CRP
Synopsys	The paper describes three propulsion combinations (with modified hull-lines) for improving the course-keeping characteristics of pod-driven configurations. The three options include: two pods; one pod close behind a conventional propulsion system (hybrid); single CRP pod. The conclusion argues that course-keeping should be the most important parameter and finds favour for the hybrid option.

42 Process of integration and fitting out of a pod

Author(s)	Chabert, C., Laurent, G., Keruel, B., Trichler, G., Le Floch, G.
Pages	Session 1
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	semi-submersible, naval application, submerged installation, wet installation
Synopsys	The paper documents design experience related to the installation of pods on semi-submersible platforms; including space optimisation and submerged installation. In addition, some discussion is made regarding the use of pods for naval application. Further, details of installation in dry-dock are given. Conclusion suggest dry-dock option has advantages but points out that situations may transpire to prevent this option and thus make wet institution necessary.

43 The pump jet pod: an ideal mean to propell large military and merchant ships

Author(s)	Bellevre, D., Copeaux, P., Gaudin, C.
Pages	Session 1
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	pump-jet, nozzle, flow-stator
Synopsys	The paper describes the action of a pump-jet pod; comprising a pod with propeller nozzle including flow-stator. Conclusions claim that the unit concept offers increased propulsive efficiency while at the same time offering a more compact unit.

44 Impact of phase lag between propeller excitation componebts on vibration of a podded propulsion vessel

Author(s)	Borowski, J., Konieczny, L., Rozbicki, M.
Pages	Session 2
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	phase-lag, propeller excitation, vibration
Synopsys	The paper cites situations wherein even sister-ships can present unexpectedly different vibration behaviour; postulating random phase-lag to be a possible cause. A method accounting for phase-lag between propeller excited pressure fluctuations, acting at different points on the hull, is described. Comparison is made with and without the correction using a fast container ship with 4 pods as case study. Conclusions argue that accurate determination of propeller induced forces is important for reliable vibration analysis.

45 Container intake increase due to pod propulsion application

Author(s)	Kanar, J., Łapiński, K.
Pages	Session 2
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	general arrangements, prime-mover selection
Synopsys	The paper considers design aspects of a fast, pod-driven, container vessel, paying particular attention to general arrangements and selection of prime-movers. Conclusions argue moderate quantitative advantages for the pod-driven option, but also comments that qualitative advantages should be considered when making judgment.

46 Development of the propeller series for Azipod compact

Author(s)	Frolova, I., Kaprantsev, S., Pustoshny, A., Veikonheimo, T.
Pages	Session 2
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	propeller series, cavitation bucket, hub-diameter
Synopsys	The paper presents the development of a propeller series data set, targeted for the Azipod compact unit, and with the aim of minimising the design process. Design curves are presented including a diagram of hydrodynamic characteristics, Cavitation bucket and the influence of hub-diameter to open water efficiency.

47 Hydrodynamic study of podded propulsors with systematically varied geometry

Author(s)	Islam, M. F., Molloy, S., He, M., Veitch, B., Bose, N., Liu, P.
Pages	Session 3
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	systematic series, pod-body/propeller ration, hub-angle
Synopsys	The paper presents results of an experimental study of the effects of geometric parameters on the propulsive characteristics of a puller-type pod. Conclusion argue that pod-body and propeller diameter ration and hub-angle have a significant impact on propeller thrust and torque and on unit thrust, over the entire range of advance values.

48 Discussion on hydrodynamic performance for podded propeller by using surface panel method

Author(s)	Lijun, Z., Yanying, W.
Pages	Session 3
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	pod-body and propeller interaction, potential code
Synopsys	The paper considers pod-body and propeller interaction using a potential-based surface panel method; including source distribution on the propeller blades, hub, pod-body and strut. Results are compared with experimental values.

49 Numerical prediction of unsteady performance of podded propeller

Author(s)	Cheng, M., Zhengfang, Q., Chen-Jun, Y., Xu, Z., Du, D., Sheng, H.
Pages	Session 2
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	vortex lattice, surface panel method
Synopsys	The paper presents a method for predicting hydrodynamic forces; using a vortex lattice method for the propeller blades and a surface panel method for the pod. Calculations are partially validated with experimental data. Conclusion states that the effect of the pod-strut wake is significant.

50 A parametric power prediction model for tractor pods

Author(s)	Flikkema, M. B., Holtrop, J., van Terwisga, T. J. C.
Pages	Session 3
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	parametric model, powering prediction, form-factor
Synopsys	The paper presents a parametric model for power prediction of ships which are propelled by tractor pods. The effect of the pod-body on the propeller performance is determined by using a form-factor; including additional factor for pressure resistance. Uncertainty is estimated and valued given.

51 HTS ship propulsion motors for podded applications

Author(s)	Kalsi, S. S.
Pages	Session 4
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	high-temperature superconductor
Synopsys	The paper discusses the merits and potential application of using high-temperature superconducting motors, within pods, to reduce motor size and thus improve hydrodynamic performance.

52 Power dense electric motor technologies for podded propulsion – FASTPOD project

Author(s)	Letellier, P., French, C.
Pages	Session 4
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	permanent magnet, synchronise motors
Synopsys	The paper considers the high-powered motors needed for the pods of two fast and large concept vessels. The paper considers radial field permanent magnet synchronise motors and investigates control technologies.

53 Study of unconventional winding configuration of multiphase permanent magnet synchronous machine to improve reliabiliy and torque quality for pod propulsion application

Author(s)	Sciuller, F., Charpentier, J. F., Semail, E., Clénet, S., Letellier, P.
Pages	Session 4
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	permanent magnet, two-star supply
Synopsys	The paper considers a design methodology for a 10-phase permanent magnet machine. It is argued that the independence between the two-star windings allows for a simple control two-star supply and a straightforward fault operation mode. Conclusions suggest the design is most suited for pods.

54 A new step in high power electrical propulsion systems with PWM converters and large induction motors

Author(s)	Flury, G., Leleu, E., Manuelle, P., Mercier, J-C., Terrien, F.
Pages	Session 4
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	high torque density, converters
Synopsys	The paper describes advancement in high power electrical propulsion system based on large high torque density induction machines fed by a new generation of medium voltage Press-Pack IGBT (PPI) converters.

55 Experance from testing of pod units in SSPA's large cavitation tunnel

Author(s)	Allenström, B., Rosendahl, T.
Pages	Session 5
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	testing, cavitation tunnel
Synopsys	The paper presents the wide experience of the title facility related to the testing and performance evaluation of pods; including details of two large-scale studies. Discussions include both conventional pod arrangements and more complex problems such as CRP configurations.

56 Cavitation tests for two fast ferries with pod-drives carried out in HSVA's large cavitation tunnel HYKAT

Author(s)	Johannsen, C., Koop, K-H.
Pages	Session 5
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	water-jet/pod combination, cavitation tunnel
Synopsys	The paper presents the wide experience of the title facility related to the testing and performance evaluation of pods; including details of two large-scale studies. Discussions include both conventional pod arrangements and more complex problems such as water jets and pods in combination.

57 Effects of thickness and cavitation on performances of hydrofoils

Author(s)	Sarraf, C., Djeridi, H., Billard, J-Y.
Pages	Session 5
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	strut section, strut cavitation
Synopsys	The paper considers aspects of performance and cavitation on pod-strut sections. Experiments are reported on a number of profiles, including high incident angles greater than stall. Conclusions argue that for cavitation, the classical relationship α and $-C_{pmin}$ is preserved regardless of boundary layer thickness.

58 Ice blockage testing with a DAT tanker podded propulsor

Author(s)	Sampson, R., Atlar, M., Sasaki, N.
Pages	Session 5
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	ice-milling, blockage, double-acting tanker
Synopsys	The paper presents blockage tests conducted to investigate cavitation and propeller performance when in an ice-milling condition; using a double-acting tanker as case study. Conclusions are drawn regarding blockage parameters and propeller efficiency.

59 Wake impingement experiments on a tractor-type podded propeller

Author(s)	He, M., Islam, M., Veitch, B., Bose, N., Colbourne, B., Liu, P.
Pages	Session 6
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	strut, pressure distribution
Synopsys	The paper presents an experimental investigation that focuses on the time-varying pressure distribution around the leading edge of the strut. Various conclusions are drawn related to performance parameters. In addition, it is argued that the presence of the pod and strut increased the propeller thrust, torque, and efficiency, but it did not significantly change the amplitudes of time varied thrust and torque coefficients.

60 Improvement of multipropulsor systems performances by pod units applications

Author(s)	Kanar, J.
Pages	Session 6
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	multiple-pods, steering-flaps
Synopsys	The paper presents extract of the most significant findings by the author facility related to research conducted within two large-scale studies. A variety of pod arrangements are presented including steering-flaps; giving strengths and weakness of each. Conclusions argue that the pod configuration offers advantage over conventional arrangements.

61 Dynamics of propeller blade and duct loadings on ventilated ducted thrusters operating at zero speed

Author(s)	Koushan, K.,
Pages	Session 6
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	duct, ventilation, immersion ratios
Synopsys	The paper considers propeller blade and duct loading fluctuations and ventilation at various immersion ratios and advance conditions. Conclusions argue that the effect of ventilation on ducted propellers is significant though the effect reduces at immersion ratios of 2.4 and larger.

62 Possibilities of a viscous/potential coupled method to study scale effects on open-water charateristics of podded propulsion

Author(s)	Krasilnikov, V., Ponkratov, D., Ahkinadze, A., Berg, A., Ying, S. J.
Pages	Session 7
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	viscous/potential, RANS
Synopsys	The paper considers a viscous/potential coupled panel method improved with viscosity corrections. The results of numerical verification of the coupled solution are presented. The numerical predictions are compared with experimental data from model tests. Scale effects on pressure and friction components of the gondola resistance are discussed.

63 Computation of the fluctuating pressure distribution on the pod strut

Author(s)	Deniset, F., Laurens, J.-M., Romon, S.
Pages	Session 7
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	potential code, Navier-Stokes, boundary element method
Synopsys	The paper presents a method of analysing the flow around a propeller and pod using a combination of potential flow code and Navier-Stokes solver; treating the strut and the pod-body independently. Conclusions argue that the numerical procedure to predict hydrodynamic forces acting on the strut proves to be fast and robust. Finds suggest that the tetrahedral mesh generates too much numerical dispersion to be used in unsteady state cases.

64 Peliminary results of a numerical method for podded propulsors

Author(s)	Bal, S., Akyildiz, H., Guner, M.,
Pages	Session 6
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	boundary element method, vortex lattice
Synopsys	The paper presents and analysis of flow around a pod with and without the strut; with the objective of predicting the performance of the propeller. The pod and strut parts are modelled by a low-order boundary element method, the propeller by a vortex lattice method. Conclusion report good agreement with experiments and with other numerical methods.

65 RANS predictions for flow patterns around a compact Azipod

Author(s)	Sánchez-Caja, A., Pylkkanen, J. V.
Pages	Session 7
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	RANS, streamlines
Synopsys	The paper presents a numerically investigated of the hydrodynamic performance of a Compact Azipod unit at full and model scale; at the design operation point. Scale effects are shown for the forces on different components of the unit. Pressure distributions and streamlines are presented to illustrate regions of 3D separation on the strut and pod.

66 An unsteady inviscid-flow model to study podded propulsors hydrodynamics

Author(s)	Greco, L., Colombo, C., Salvatore, F., Felli, M.
Pages	Session 8
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	vortex/wall, wake alignment
Synopsys	The paper presents a numerical methodology for the hydrodynamic analysis of pod propulsion. Formulation is based on a boundary integral equation method; using a wake alignment technique and a vortex/wall impingement model to describe the propeller trailing wake and its interactions with the regions of the strut. Numerical results are presented to validate the trailing wake alignment procedure and the wake/wall impingement model.

67 Reliability and redundancy analysis of a large, high-speed vessel fitted with pod propulsion system

Author(s)	Aksu, S., Turan, O., Aksu, S., Letellier, P., Bonneau, C.,
Pages	Session 8
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	reliability, redundancy analysis, fault-tree-analysis
Synopsys	The paper discusses the development of a probabilistic reliability assessment methodology applied to a high-speed large pod-driven Ropax vessel. The study also covers redundancy analysis, which comprises of different failure modes in thrust, pod rotation or the combination of both. The results have been assessed within the context of a Fault Tree Analysis and Markov Analysis techniques to identify reliability boundaries for system during the operation.

68 Estimation of roll damping characteristics of pod propulsion structure

Author(s)	Ayaz, Z., Turan, O.
Pages	Session 8
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	roll damping, heeling angles
Synopsys	The paper presents experimental results for the measurement of forces and moments on a vessel while varying helm angle of the pods. Steady heeling angles caused by turning are measured. The roll damping characteristics of pods, with fin attachments, are also investigated. Conclusions suggest, among other things, that the form of the pod should affect roll damping.

69 The propulsive performance of a podded propulsion ship with different shape of stern hull

Author(s)	Ukon, Y., Sasaki, N., Fujisawa, J., Nishimura, E.
Pages	Session 8
Year	2006
In	Second Int. Conf. on Technological Advances in Podded Propulsion (T-POD 2006)
City	L'Aber Wrac'h, France
Publisher	Organising Committee (Published only in electronic form)
Key words	stern bulb, buttock flow stern, scale-effects
Synopsys	The paper discusses the propulsive performance of pod-driven ships with buttock flow stern hull and stern bulb hull form, comparing with that of the conventional propulsion ship for a 26,000-deadweight tonnage product carrier. The conclusions find that the bulb hull is one of the promising options to enhance not only the propulsive performance but also manoeuvrability. Also, the correction on the scale effects for pod propulsors reduces 3-8% of the required horsepower.

70 A study on manoeuvrability standards for a ship with pod prpoulsion

Author(s)	Haraguchi, T., Nimura, T.
Pages	RB-3-1 to 8
Year	2003
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'03
City	Kanazawa, Japan
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	spiral-loop width, zig-zag manoeuvres
Synopsys	The paper examines the relationship between spiral-loop width and overshoot angles for a modified zig-zag, by simulation; for both conventional and pod-driven arrangements. Various conclusions are drawn regarding the relationship between 10-10 and 20-20 zig-zag manoeuvres for conventional and pod-driven ships

71 On the manoeuvring prediction of pod-driven ships

Author(s)	Woodward, M. D., Clarke, D., Atlar, M.
Pages	RB-7-1 to 9
Year	2003
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'03
City	Kanazawa, Japan
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	semi-empirical tools, pod derivative
Synopsys	The paper presents semi-empirical tools developed to account for the pram stern-form; typical of pod-driven ships. In addition, method of estimating the pod derivative contribution is derived. Validation is made by comparing predicted derivatives with captive tests and performance with free-running tests.

72 Prediction of the manoeuvrability on twin podded vessel

Author(s)	Yan, H-J., Kwon, C-S., Lee, Y-J. Park, G-I.
Pages	M-177 to M186
Year	2009
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'09
City	Panama City, Panama
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	captive tests, free-running tests, full-scale trials, sea-trials
Synopsys	The paper describes the design, and testing of an Arctic Shuttle Tanker, which has twin Azipods; including development of hydrodynamic model, captive and free-running testing. Test results are compared with sea-trials. Conclusion find that, for advance and tactical diameter, the captive tests proved better predictive results than the free-running tests. Pod unit thrust, normal force and steering torque were measured in the free-running model tests and found to reflect real physical phenomena found in the simulations.

73 Hydrodynamic forces investigation on a ship with azimuthing propellers in maneuvering motions

Author(s)	Susumu, T., Noritaka, H., Hironori, Y.
Pages	M-187 to M-196
Year	2009
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'09
City	Panama City, Panama
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	pusher- and puller-modes, course-stability, captive tests, free-running tests
Synopsys	The paper describes an experimental study including captive and free-running model tests conducted on a ship with twin pods; considering both pusher and puller modes of operation. Conclusions claim that the puller-mode offers superior performance in terms of both control-force and course-stability. Mathematical models regarding inflow velocities are derived.

74 A new chapter unfolding: Can High-speed Commercial Ships be Effectively Driven by Pods?

Author(s)	Atlar, M.
Pages	52 slides
Year	2004
In	The 4th Intl. Ship Propulsion Systems Conference - Lloyd's List Events,
City	Manchester, United Kingdom
Publisher	Lloyd's Register of Shipping (Note: PP presentation only)
Key words	FASTPOD, commercial ships
Synopsys	The presentation presents and overview of current pod technology (at the time) and the objectives of the FASPOD project (an EU funded project under Framework 5). The FASTPOD objective was to investigate the application of pod drives on large and fast commercial ships in an efficient, safe and environmentally friendly manner.

75 Reliability and availability of pod propulsion systems

Author(s)	Aksu, S., Aksu, S., Turan, O.
Pages	41 to 58
Year	2006
In	J. of Quality and Reliability Engineering International, Vol. 22, Issue 1,
City	N/A
Publisher	Wiley – Inter Science
Key words	failure-mode, effect-analysis, fault-tree-analysis, Markov-analysis
Synopsys	The paper presents a reliability assessment methodology and its application to a combined four-pod propulsion system on a vessel equipped with two fixed and two rotating pod units. Failure Mode and Effect Analysis, Fault Tree Analysis and Markov Analysis have been utilised in the developed methodology. The developed methodology claims to have identified the reliabilities of the pod propulsion system and its components, and shown good agreement in general with the accepted criteria suggested by the manufacturers.

76 Manoeuvring and seakeeping aspects of pod driven ships

Author(s)	Ayaz, Z., Turan, O., Vassalos, D.
Pages	77 to 92
Year	2005
In	J. of Engineering for the Marine Environment – Vol. 219, No. 2
City	N/A
Publisher	Proc. Int. Mechanical Eng. – Part M
Key words	seakeeping, simulation, manoeuvring in waves
Synopsys	The paper presents a non-linear 6-dof model combining manoeuvring and seakeeping; enhanced for the motion simulation pod-driven ships. The code is verified using experimental data for both conventional and pod-driven Ropax hull-forms. Comparisons are made using zigzag and pull-out manoeuvres and significant motion amplitudes in waves; with the aim of investigating the course-keeping ability, the effect of large pod-induced heel angles on the turning and ship motions in waves. Stability and control problems caused by design modifications are demonstrated using the numerical simulations.

77 Numerical assessment of operational behaviour of high-speed, pod-driven large ships

Author(s)	Ayaz, Z., Turan, O., Vassalos, D.
Pages	9 pages
Year	2005
In	Int. Conf. on Maritime Transportation and Exploitation of Ocean and Coastal Resources - IMAM05
City	Lisbon, Portugal
Publisher	IMAM Organising Committee
Key words	seakeeping, course-stability in waves, broaching, parametric rolling
Synopsys	The paper presents background of enhanced 6-dof numerical model for pod-propulsion; including a parametric study of these vessels in terms of manoeuvring, which looks at turning, directional stability and heeling angles due to manoeuvring at high speed, the redundancy analysis. Also seakeeping is investigated for directional stability characteristics and possible dangerous conditions that may occur such as broaching-to and parametric rolling in extreme wave conditions.

78 Podded propulsors for fast and large commercial vessels (FASTPOD project)

Author(s)	Depascale, R., Atlar, M., Woodward, M. D.
Pages	6 pages
Year	2005
In	Int. Conf. on Fast Sea Transportation - FAST'2005
City	St. Petersburg, Russia
Publisher	Conference Organising Committee
Key words	FASTPOD, fast ships
Synopsys	The paper provides an overview of the FASTPOD (EU funded project under Framework 5) project highlighting the design problems encountered and the solutions worked out. Some results of the FASTPOD technology are presented evaluating advantages/disadvantages, benefits and risks related to the application of pod propulsion to fast vessels.

79 Optimization of podded propulsor for fast ropax using RANS solver with cavitation model

Author(s)	Sànchez-Caja, A., Pylkkänen, J. V.
Pages	6 pages
Year	2005
In	Int. Conf. on Fast Sea Transportation - FAST'2005
City	St. Petersburg, Russia
Publisher	Conference Organising Committee
Key words	FASTPOD, RANS, FINFLO, cavitation
Synopsys	The paper reports on pod designs with speeds in the range of 35-38 knots; investigating hydrodynamic design of the propellers with its housing – considered critical due to the appearance of cavitation both on the propeller blades and pod housing. The paper deals with the design process of the propeller and housing using RANS solver FINFLO. A one-phase cavitation model is implemented, which combines a linearized kinematic boundary condition for the tangential flow at the bubble surface with a constant pressure boundary condition in the cavitation bubble.

80 Manoeuvring induced loads on fast pod drives

Author(s)	Woodward, M. D., Atlar, M., Clarke, D.
Pages	8 pages
Year	2005
In	Int. Conf. on Fast Sea Transportation - FAST'2005
City	St. Petersburg, Russia
Publisher	Conference Organising Committee
Key words	spike-loads, dynamic manoeuvring loads
Synopsys	The paper presents results wherein model tests on a 4-podded and a 2-podded Ropax identified significant spike-loads when operating the pods for manoeuvring. This paper describes the formulation of a suitable simulation algorithm for predicting these peak loads; validated by comparison with free-running model tests. Results are presented together with a sensitivity analysis of both the physical and operational parameters that most affect the spike loads. Conclusions are drawn as to the implications for design and operation of pods driven ships.

81 Fast ship applications for pod drives - A European sponsored project

Author(s)	Woodward, M. D.
Pages	71 slides
Year	2005
In	RINA London branch public lecture, Lloyd's Register (Note: PP presentation)
City	London, United Kingdom
Publisher	N/A
Key words	FASTPOD
Synopsys	The presentation presents and overview of FASPOD project (an EU funded project under Framework 5). The FASTPOD objective was to investigate the application of pod drives on large and fast commercial ships in an efficient, safe and environmentally friendly manner.

82 Comparison of stopping modes for pod driven ships by simulation based on model testing

Author(s)	Woodward, M. D., Atlar, M., Clarke, D.
Pages	47 to 64
Year	2005
In	J. Engineering for the Marine Environment – Vol. 219, No. M2 (ISSN 1475-0902)
City	N/A
Publisher	IMarEST
Key words	crash-stop, indirect stopping mode
Synopsys	The paper considers various options that may be used to stop a pod-driven ship. A continuous function is derived describing the hydrodynamic forces on both the propeller and the pod-body for any load condition and helm angle, including fluid damping and added mass effects; validated through comparison with free-running model tests. A time domain simulation algorithm is proposed to examine the dynamic effects including the mass inertia on both the propeller shaft and slewing stock. A simulation is performed using a known design as a case study. Conclusion find an 'indirect-mode' stops the ship quickest.

83 Pods – Guidance for the practicing Naval Architect

Author(s)	Woodward, M. D., Atlar, M.
Pages	49 to 56
Year	2006
In	J. of Marine Design and Operation
City	N/A
Publisher	Proceedings of The Institute of Marine Engineering, Science and Technology
Key words	design, design-spiral, naval architecture
Synopsys	The objective of this paper is to give the practicing naval architect general background into the technology and to highlight key issues applicable to the design of pod-driven ships. Influential disciplines on the design spiral are identified and discussed in the context of both preliminary and more general design issues.

84 Application of the IMO manoeuvering criteria for pod-driven ships

Author(s)	Woodward, M. D., Atlar, M., Clarke, D.
Pages	106 to 120
Year	2009
In	J. of Ship Research
City	N/A
Publisher	The Soc. Of Naval Architects and Marine Engineers
Key words	IMO criteria, Resolution MSC.137(76)
Synopsys	The objective of the paper is to make assessment of the validity of the IMO manoeuvring criteria 'Resolution MSC.137(76)', when applied to pod-driven ships., New methods for modelling the hydrodynamic reaction for both the ship-hull and pod-drive are identified. A dedicated numerical tool is developed and simulation study conducted exploring systematic variation of applied helm angles with comparison of time- and frequency-domain responses. The study reaches the conclusion that, the criteria provides equivalent information about the manoeuvring response of pod-driven ships as for conventionally propelled ships; and can thus be applied directly.

85 Intuative operation and pilot trainging when using marine azimuthing control devices - AZIPILOT

Author(s)	Landamore, M., Woodward, M. D.,
Pages	39 to 46
Year	2009
In	Int. Conf. Human factors in ship design and operation
City	London, United Kingdom
Publisher	Royal Institution of Naval Architects
Key words	AZIPILOT, human factors
Synopsys	The paper gives an overview of the aims and objectives of the AZIPILOT project (EU funded project under FP7) and summarises the work so far. The project aims to improve, by policy and design, the safety and security of ships, considering the man-machine interface and the training of maritime pilots; specifically when operating ships equipped with azimuthing control devices. To address the problem, AZIPILOT brings together specialists in Hydrodynamic Modelling, manufacturers of Marine Simulators, Maritime Training facilities and practitioners in Operation Practice.

86 The moving mathematical models of tug with Voith Schneider propellers

Author(s)	Xiufeng, Z., Yong, Y., Yicheng, J.
Pages	DVD ROM [File > Modelling]
Year	2006
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'06
City	Treschelling, the Netherlands
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	Voith Schneider, simulation, training
Synopsys	The paper presents a 3-dof moving model of a tug equipped with Voith Schneider Propellers (VSP). Introducing also a moving mathematical model of a tug into a Ship Manoeuvring Simulator. The paper claims that, despite some minor differences between the results of the simulating tests and those of the ship sea trials, the models can perfectly satisfy the demands of teaching and training.

87 Development of a mathematical model of a Voith Schneider tug and experience from its application in an offshore simulation study

Author(s)	Agdrup, K., Olsen, A. S., Jürgens D.
Pages	DVD ROM [File > Modelling]
Year	2006
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'06
City	Treschelling, the Netherlands
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	Voith Schneider, tug, validation, simulation
Synopsys	The paper describes the development of a mathematical model of a tug with Voith Schneider Propellers. PMM tests were performed; carried out with the hull without propellers but including propeller guard, both with and without the fin. The wind loads were estimated using the database of wind tunnel test data. The mathematical model was validated by having an external tug master sail the tug model in the simulator.

88 Prediction of the manoeuvrability on a ship with a CRP pod propulsion system and an auxiliary rudder

Author(s)	Haraguchi, T., Kayano, J., Tsukadn, Y.
Pages	DVD ROM [File > Modelling]
Year	2006
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'06
City	Treschelling, the Netherlands
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	contra-rotating, advance, tactical diameter, overshoot
Synopsys	The paper describes a project to develop a coastal ship with a CRP (Contra-Rotating Propeller) pod propulsion system. Conclusions report that from the results the steady turning motions can be predicted by the proposed method but the advance, tactical diameter and overshoot angles are not necessarily predicted. Also, that the flow straightening coefficient, the interference coefficient between hull and pod and the interference coefficient between pod and rudder need more investigation.

89 Thruster-thruster interaction for manoeuvrability evaluation

Author(s)	Reinders, S., Grimmelius, H. T., Ligtelijn, J. T., Moulijn, J.
Pages	DVD ROM [File > Modelling]
Year	2006
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'06
City	Treschelling, the Netherlands
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	thruster-to-thruster interaction, ASD, simulation
Synopsys	The paper considers the interaction between two azimuthing thrusters when they operate in close vicinity, as for instance is the case with ASD tugs. A concept exploration model for manoeuvrability was developed, intended to be used in the preliminary design stage; allowing for both pre-defined (standard) and custom manoeuvres. The paper gives a general introduction to simulation model and describes its main features; including the modelling of thruster-thruster interaction .

90 On manoeuvring and control of large high-speed pod driven ships in waves

Author(s)	Ayaz, Z., Turan, O.,
Pages	DVD ROM [File > Modelling]
Year	2006
In	Int. Conf. on Marine Simulation and Manoeuvrability – MARSIM'06
City	Treschelling, the Netherlands
Publisher	MARSIM Organising Committee (see also: International Marine Simulation Forum)
Key words	seakeeping, high-speed ships
Synopsys	The paper presents the enhancement of an existing 6-dof non-linear numerical model, which combines manoeuvring and seakeeping, with the high-speed multi-pod drive control and thrust units. The numerical model is validated using a Ropax and Containership, which are both high-speed large pod-driven ships of which very extensive manoeuvring and seakeeping test data are available. Followed by a parametrical analysis for various operation and design conditions.

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Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title:

Deliverable 1.1: Distilled Manoeuvring hydrodynamics

Contents

Introduction

The aim of this task is to review existing hydrodynamic knowledge with respect to the ability to model azimuthing control devices. The objective is to survey available and ongoing sources of information and in doing so to compile a database of existing capabilities. The main areas of focus for this report is to survey outcomes and recommendation from past projects. Specifically, the report will attempt to summarise the main manoeuvring related hydrodynamic knowledge obtained from European projects; funded under the framework programs.

Additional information will appear on post-it notes like this one.

1 Overview of relevant framework funded projects

There have to date been three medium sized projects, funded under the EU framework program, that have focus on azimuthing control devices (ACD). More specifically, the three projects in question considered the design and operation of pod-driven ships. Namely: *Pods-in-Service*; *OPTIPOD*; *FASTPOD*. Each project had a significant proportion of its work dedicated to the investigation of the manoeuvring behaviour of such ships and it thus relevant to this study. The following sub-sections summarise the general and more specific aims and objectives of each named project.

1.1 Pods-in-Service

Pods-in-Service – *"Safety and reliability of podded propulsors under service conditions"*, was a three-year project starting in January 2000 and ending in December 2003. The project brought together 12 partner organisations and was funded under FP5. At the time of commencing, little was known about the true nature of loads on pod-driven ships. Highlighting this, the project mission states:

"Podded propulsors for ships offer significant economic, safety and environmental advantages but their behaviour in service conditions i.e. in extreme weather, emergency manoeuvres and due to long term loading, is yet unknown. This project is aiming at the development of design, engineering and certification methods for extreme, fatigue and incident loads in pods and ship. To this end an extensive full-scale monitoring campaign onboard three ships will be conducted during their operations. The measured loads together with laboratory research on specific cases will be used to develop and validate the load calculation models methods and standards. These results will be implemented in the design, engineering and certification by the involved pod manufactures, yards and classification societies."

Clearly, from the above, the project had a significant potential to address many problems that have beset pod-driven ships; both then and today. However, due to the commercially sensitive nature of the project data, nothing has been published in the public domain. In fact, as the project included more than one pod-manufacture, much non-disclosure was implemented. This was achieved by Class Society partners, within the project, acting as the points of contact for data analysis. Consequently, at the time, no data was made available to the wider audience.

Nevertheless, the Framework Program contracts are such that project deliverable must become available in the public domain, 5-years after the project has ended. With this in mind, it was the aim of this project to extract any useful data from the Pods-in-Service deliverables, being as they should be, now available.

Unfortunately, all data from Pods-in-Service seems to be hidden in red tape.

Unfortunately, efforts made to obtain the project deliverables have been, to date, unsuccessful; yielding no responses. While there is always the possible that some data may become available, it is here considered unrealistic to rely on such for this project. Nevertheless, attempts to obtain the data will continue.

1.2 OPTIPOD

OPTIPOD – *"Optimal design and implementation of azimuthing pods for a safe and efficient propulsion ships"*, was a three-year project starting in January 2000 and ending in December 2003. The project brought together 14 partner organisations and funded under FP5. The project focus was on the design of pod-driven ships; considered as is necessary, a wide variety of subject disciplines. The project was divided into 9 work packages; looking into all aspect of design. Specifically of interest to this project, work package 3 considered *"Safety and risk analysis"*, considering the manoeuvring related issues.

The objective of WP3 was to identify possible risks associated with the application of the pod propulsion systems to various ship types concerning their manoeuvrability, course-keeping and power redundancy, and to propose appropriate measures to control the associated safety and risk. The work was broken into 7 sub-tasks outlined below.

OPTIPOD had a whole work package devoted to manoeuvring Safety & Risk

The first task covered the development of theoretical tools and their validation, for predicting the manoeuvring derivatives of pod-driven ships. This included the development of semi-empirical tools, validation of such tools by comparison with both captive model test results and CFD studies (using four case-study ship designs). The second and third task encompassed an extensive captive testing program and free-running testing program (respectively) using the four designs: a cruse ship; a cargo ship; a Ropax; a supply vessel. The fourth task performed simulation studies of the IMO criteria for the four ship types, using the results to better understand how such ship comply or otherwise with these criteria. The fifth task conducted full-scale sea-trials using a pod-driven ship (not one of the four case-study ships). The sixth task used the gained knowledge to propose optimal designs. Finally, the seventh task looked into the power redundancy; exploring, among other things, the implications of a loss of steering or propulsion components.

Much understanding regarding the manoeuvring behaviour of pod-driven ships was gained within this project; and carried through to the FASTPOD project (described next). Consequently, much of the distilled work reported herein is derived from the foundation work performed within OPTIPOD.

1.3 FASTPOD

FASPOD – *"Fast ship applications for pod drives"*, was a three-year project starting in January 2002 and ending in December 2005. The project brought together 17 partner organisations and funded under FP5.

The primary objective was to exploit benefits that can be offered when using electric podded drives on commercial large and fast ships in an efficient, safe and environmentally friendly manner. The viability of the FASTPOD technology was demonstrated through both theoretical and experimental methods using case study ships including a Ropax, a cargo ship and an advanced platform concept. The project was divided into 5 technical work packages covering the subject of: Concept exploration; Hydrodynamic design; Engineering design; Operational and economic aspects; Validation. The main work package of interest herein in the Hydrodynamic design. This study included much hydrodynamic testing including both captive and free-running model tests. Also of interest is the work carried out in the Validation work package, wherein the very real nature of the theoretically predicted phenomenon are demonstrated.

FASTPOD identified large spike-loads on the pods when manoeuvring.

Again, much understanding regarding the manoeuvring behaviour of pod-driven ships was gained within this project. Consequently, much of the distilled work reported herein is derived from the foundation work performed within FASTPOD.

2 Overview of the layout of this report

The volume hydrodynamic research and results generated within OPTIPOD and FASTPOD is very large indeed. Nevertheless, much of the useful information has since been distilled into a published form. This report makes use of this data and distils further the salient points. This still results in a significant volume of materials however the content is broken into three sections to make it, hopefully, easer to digest:

- Implications for the IMO criteria;
- Manoeuvring induced loading;
- Reliability assessment.

Each is broken into sub-sections however the first points provides the main body of the report; the second and third relying/referring heavily on the content of the first.

Implication for the IMO criteria

The following section describes in brief and makes critical assessment of the requirements for ship manoeuvring performance, defined through the use of specific criterion as specified by the International Maritime Organisation – Interim standards for ship manoeuvrability; for full text readers are referred to IMO (2002). The standards should be applied to all ships of all rudder and propulsion types, of 100 meters in length and over, and chemical tankers and gas carriers regardless of length. The standard manoeuvres should be performed without the use of any manoeuvring aids, which are not continuously and readily available in normal operation.

This section summarises the main findings of a Ph.D. thesis investigating the control and response of pod-driven ships; Woodward (2005). The work presented was conducted in collaboration with both OPTIPOD and FASTPOD. The objective of the study was to assess the applicability of the IMO manoeuvring criteria for pod-driven ships. It is not the specific claim of the study that is can make very accurate performance prediction; dealing as it does with only principal dimensions and coefficients as input. Nor does the study make any judgment on the validity of the IMO manoeuvring criteria as an effective measure of the manoeuvring performance of ships. Specifically, the objective of the study is to establish if the recommended manoeuvres, when applied to pod-driven ships, ask the same questions about manoeuvring performance and if so give equivalent answers.

Can the IMO manoeuvring criteria be applied to pod-driven ships?

The approach of the study is to consider the sensitivity of the manoeuvring criteria parameters to the principal dimensions and coefficients and to the control inputs, and thus study makes assessment of the equivalents of the IMO manoeuvring criteria; when applied directly to pod-driven ships. First, methods are identified for estimating the hull-form derivatives; suited to the hull-forms typical of pod-driven ships. Next, a numerical description of the pod is given, taking into account the effects of propeller inclination and the subsequent flow over the pod-body. A description of the developed algorithm for time-domain numerical simulation is provided; delineating the contributing factors. Next, the simulation algorithm is validated by comparison with free-running model tests for three different pod-driven ships. Finally, using the validated simulation tool, a parametric analysis is made examining the characteristic performance of pod-driven ships when executing the required manoeuvres – and definitive conclusions are drawn.

3 Critical appraisal of the IMO criteria

The International Maritime Organisation (IMO) acknowledged the importance of ship manoeuvrability standards with, in 1968, the adoption of Resolution A168(IV) 'Recommendation on Data concerning Manoeuvring Capabilities and Stopping Distances of Ships'. In 1993, the IMO introduced Resolution A.751(18) 'Interim Standards for Ship Manoeuvrability'; applicable to all ships of all rudder and propulsion types, of 100 meters in length and over, and chemical tankers and gas carriers regardless of length, which are constructed on or after 1st July 1994 (IMO, 1993, 1993a). Following the introduction of these standardised sea-trails, some 499 full-scale results were compiled and used as basis for discussions on appropriate revisions to the Interim Standards (IMO, 1999, 2000, 2000a, 2000b, 2000c, 2001). In light of the findings, the 76th meeting of the IMO Maritime Safety Committee adopted Resolution MSC.137(76) 'Standards for Ship Manoeuvrability'; (IMO, 2002, 2002a). Since the adoption of the Standards for Ship Manoeuvrability, additional revisions were made regarding the stopping of very large ships; (IMO, 2004a).

The standard manoeuvres should be performed without the use of any manoeuvring aids which are not continuously and readily available in normal operation. In order to evaluate the performance of a ship, manoeuvring trials should be conduced to both port and starboard and at the following test conditions:

- deep, unrestricted waters;
- calm environment;
- full load, even keel condition;
- steady approach at the test speed

The test speed used in the standards is a speed of at least 90% of the ship's speed corresponding to 85% of the maximum engine output.

3.1 Turning Circle Criterion

For a conventional vessel, the turning circle manoeuvre is to be performed to both port and starboard with 35^{o} helm angle or maximum helm angle permissible at the test speed, following a steady approach with zero yaw-rate.

When performing this test, the advance should not exceed 4.5 ship lengths. Where, the advance is the distance travelled in the direction of the original course by the mid-ship point of a ship – from the position at which the helm order was given – to the position at which the heading has changed by 90^{o} from the original course; [See: Fig. 1]. Also, the tactical diameter should not exceed 5 ship lengths. Where, the tactical diameter is the distance travelled by the mid-ship point of a ship – from the position at which the helm order was given – to the position at which the heading has changed by 180^{o} from the original course. It is measured in the direction perpendicular to the original heading of the ship.

Current literature would indicate that the turning circle parameters are easily obtainable with existing pod-driven ships. In fact, Kurimo (1998) suggests that the traditionally defined parameters become so small that a more relevant description of the resulting turn could be based on a 'Sweep-area'. However, there is really no question of the applicability of the Advance and Tactical Diameter requirements After all, these limits clearly define a benchmark operational envelope for any ship type; irrespective of how the control force is applied.

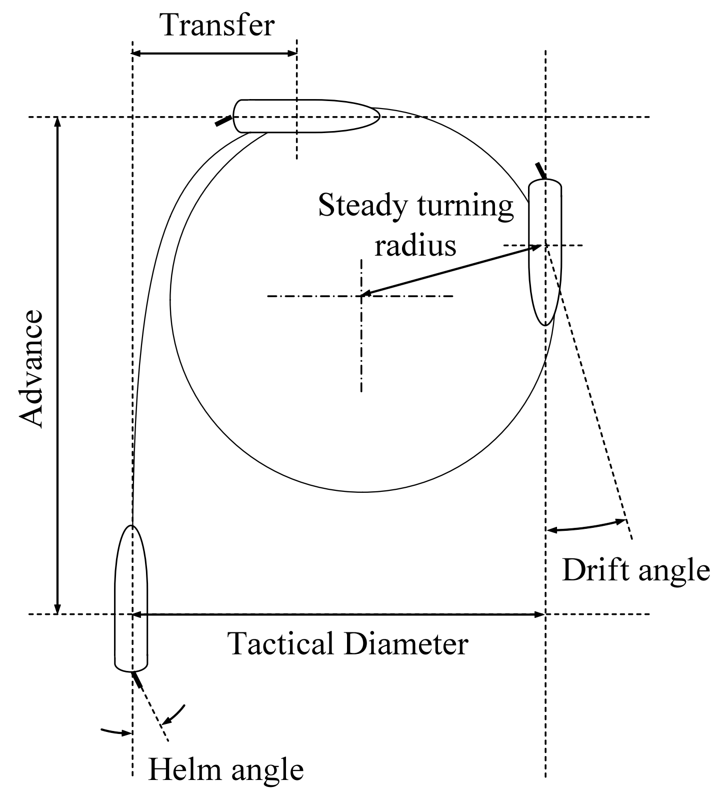
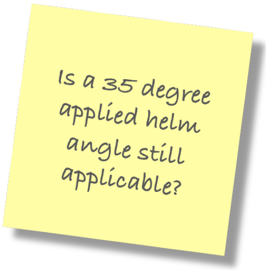


Fig. 1 – Schematic of turning circle test

What is perhaps less clear is the specific application of helm angle for an azimuthing pod-drive. A conventional rudder will provide a control force up to a certain angle of attack; beyond this angle flow separation occurs. The application of the 35° helm angle for the turning manoeuvre assumes that the maximum control force available is when the helm is hard across. However, an azimuthing pod-drive can be rotated to any angle creating a greater or lesser degree of control force; 35° therefore has little meaning when you have 360° to choose from. In fact, the complex hydrodynamic interaction between the propeller and the pod-body would suggest that the control force is a function of many parameters including ship speed, yaw rate, propeller rpm and the helm angle. In the event of an emergency it is not immediately clear, for the pilot of a pod-driven ship, which helm-angle would produce the fastest manoeuvring response.



3.2 Initial Turning Criterion

The initial turning test requires that, with the application of 10° helm angle to port or starboard, the ship should not have travelled more than 2.5 ship lengths by the time the heading has changed by 10° from the original heading; see Fig. 2.

The Initial Turning manoeuvre is essentially a measure of the transient state response to a specific helm input. A certain level of directional course-stability is necessary for the safe and practical operation of a ship, however excessive course-stability or 'super stability' will result in a ship that is difficult to turn.

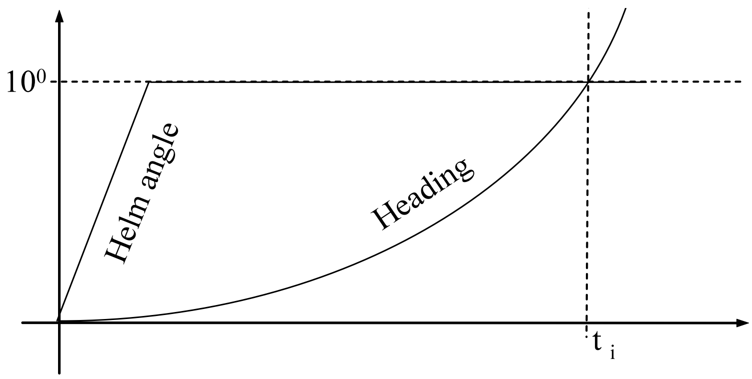
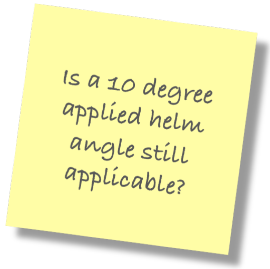


Fig. 2 – Schematic of initial turning test

The Initial Turning manoeuvre is also significantly influenced by the time-domain response of the steering gear. Generally speaking, the mass of an azimuthing pod-drive is about six times larger than the corresponding rudder – making the slewing acceleration far more influential. Also, as with the turning manoeuvre, the definition of helm angle is less clear. The specified 10^{o} applied helm angle amounts to about 25~30% of the total control force afforded by a typical rudder. In comparison, it is not entirely clear if a 10^{o} applied helm angle amounts to a greater or lesser proportion of the control force developed by an azimuthing pod-drive.



3.3 Yaw Checking Criterion

The yaw-checking test is the manoeuvre where a known amount of helm is applied alternatively to either side when a known heading deviation from the original heading is reached. For example, the 10/10 zig-zag manoeuvre is performed by turning the helm alternatively by 10^{o} to either side following a heading deviation of 10^{o} from the original heading; see Fig. 3.

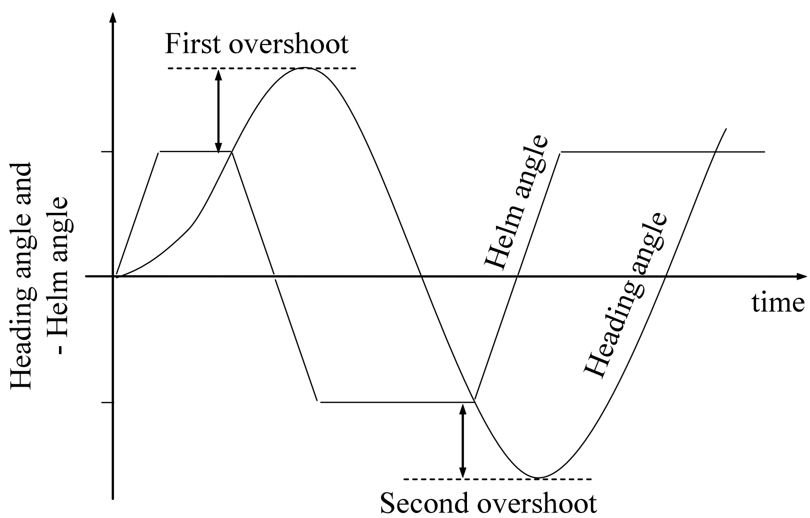


Fig. 3 – Schematic of yaw-checking test

- The value of the first overshoot angle in the 10/10 zig-zag test should not exceed: 10^{o} if (L/u) < 10 seconds; 20^{o} if (L/u) > 30 seconds; (5+ ½ (L/u)) degrees if 10 > (L/u) > 30 seconds
- The value of the second overshoot angle in the 10/10 zig-zag test should not exceed: 25^{o} if (L/u) < 10 seconds; 40^{o} if (L/u) > 30 seconds; (17.5+ ¾ (L/u)) degrees if 10 > (L/u) > 30 seconds
- The value of the first overshoot angle in the 20/20 zigzag test should not exceed 25^{o}.

The zig-zag (or Kempf) manoeuvre, first proposed by Kempf (1932) to enable testing within the confines of a towing tank, gives some measure of the transient response of the ship. Nomoto et al. (1957) shows how the equations of motion can be re-arranged from two first-order simultaneous equations in two variables, into two second-order simultaneous equations in one variable. The result gives equations in a Time and Gain constant format and allows useful experiment when measuring only the yaw rate – yaw rate being far easier to measure than sway acceleration. Using the Time and Gain constant format, Clarke (1992) demonstrates how the response of the ship is described by the Phase and Gain of the closed loop system. This however was considered too complicated a concept for regular application, and the zig-zag manoeuvre was adopted as a close approximation. Later, Clarke and Yap (2001) go on to demonstrate, using criteria maps, that the standard zig-zag manoeuvres provides a good approximation of the Phase-margin for the closed loop system; thus vindicating the initial approximation. As with the other tests, it is not entirely clear how appropriate the specified 10^{o} or 20^{o} applied helm angle requirement is for an azimuthing pod drive. Further, though the overshoot criteria have been demonstrated to make a good approximation of the closed loop Phase-margin for conventionally propelled ships, no such validation yet exists for the case of a pod-driven ship.

Do the required overshoots still approximately correspond to -5 deg. phase?

3.4 Stopping Criterion

The full-astern stopping test determines the track reach of the ship from the time the order for full-astern is given until the ship stops in the water. The track reach is the distance along the path described by the mid-ship point of a ship measured from the position at which an order for full-astern is given to the position at which the ship stops in the water. The track reach in the full-astern stopping test should not exceed 15 ship lengths; Fig. 1.10. However, this value may be modified by the Administration where ships of larger displacement make this criterion impractical, but should in no case exceed 20 ship lengths.

Is reversing RPM still appropriate or should we do something else?

While it is still perfectly satisfactory to reverse the shaft rotation on an azimuthing pod drive, we are now presented with other options for stopping that may be more effective or less demanding on the propeller. Clearly, the first variation would be to turn the pod around without reducing rpm. While running the propeller in a highly overloaded condition it would at least be operating in the correct sense of rotation. Boushkovsky et al. (2003) reports that this manoeuvre may cause dangerously high blade stresses and claims that a 60% reduction in MCR can ensure safe propeller operation. A further option would be to imitate the tug operation known as 'the indirect mode'. For example, both pods could be turned in opposite directions to say, 30o helm, using the generated lift as a breaking force; described by Woodward et al. (2005). Finally, a stopping manoeuvre involving a tight turn could be implemented, as described by Kurimo (1998), which would stop the ship with far less head reach but much increased deviation.

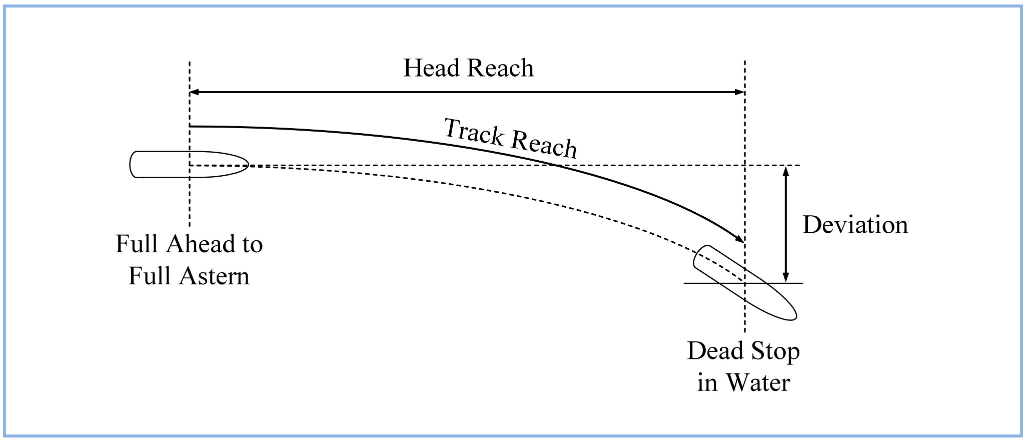


Fig. 4 – Schematic of stopping test

4 Hydrodynamic Modelling

Generally speaking, there are three fundamental differences between the hydrodynamic interaction for conventional and pod-driven ships. First, the hull-form may be significantly modified. Second, the propeller can be placed at an angle-of-attack. Third, the pod-body is heavily influenced by the modified propeller wake. The following section describes how each of these issues is accounted for in the numerical simulation model.

4.1 Hull-form

In practice, the introduction of azimuthing pod drives 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. With conventional hull-forms, the central skeg or deadwood acts in many ways like the tail fin on an aircraft; serving as a stabilising influence on the overall system. However, the more prammed stern-form, common to pod-driven ships, may have much of this skeg removed. Similar prammed stern-forms have been experimented with in the past, for various reasons, and are well known to present a tendency for low course-stability.

Changing the stern shape to make room for the pods makes the hull-form directionally unstable

At the preliminary design stage it is common practice to use semi-empirical equations to predict the manoeuvring derivatives for the ships hull-form. Woodward et al. (2003) presents semi-empirical equations specifically derived to account for the prammed stern-form, common to pod-driven ships. These equations were obtained by regression analysis from a compiled database of some 70 model-tests results [See Fig. 5 to Fig. 8]. These equation are used here as input for the numerical simulation and to implement parametric variation of the hull-form. Specifically, the velocity derivatives are obtained from Eq. 1 to Eq. 4.

$$\frac{Y'_v}{-\pi(T/L)^2} = 1.0 + 6.4\frac{B}{L} + 4.9\frac{\sigma_a B}{L} - 108.3\frac{TB}{L^2}$$ *Eq. 1*

$$\frac{N'_r - m'x'_G}{-\pi(T/L)^2} = 0.4 - 1.7\frac{C_B B}{L} + 1.3\frac{\sigma_a B}{L} - 1.7\frac{C_B x_G B}{LT}$$ *Eq. 2*

$$\frac{Y'_r - m'}{-\pi(T/L)^2} = -0.7 + 2.1\frac{B}{L} + 0.6\frac{C_B B}{L} - 0.4\frac{D}{T}$$ *Eq. 3*

$$\frac{N'_v}{-\pi(T/L)^2} = 0.8 - 1.8\frac{\sigma_a B}{L} - 0.3\frac{D}{T}$$ *Eq. 4*

The acceleration derivatives are obtained from Eq. 5 to Eq. 8.

$$\frac{Y'_{\dot v} - m'}{-\pi(T/L)^2} = 0.66 - 0.43\frac{B}{L} - 3.62\frac{\sigma_a B}{L} + 1.60\frac{C_B B}{T}$$ *Eq. 5*

$$\frac{N'_{\dot r} - I'_Z}{-\pi(T/L)^2} = 0.04 - 0.02\frac{B}{T} - 0.38\frac{\sigma_a B}{L} + 0.08\frac{C_B B}{T}$$ *Eq. 6*

$$\frac{Y'_{\dot r}}{-\pi(T/L)^2} = 0.67\frac{B}{L} - 0.0033\left(\frac{B}{T}\right)^2$$ *Eq. 7*

$$\frac{N'_{\dot v}}{-\pi(T/L)^2} = 1.1\frac{B}{L} - 0.041\frac{B}{T}$$ *Eq. 8*

Equations 1~8 were validated [reported in Woodward et al. (2003)] using the three ship designs described in Table 1 (which were not members of the original data set) and demonstrated very good comparison with captive model test results. It is considered unrealistic to make any useful prediction of higher-order terms using only principal dimensions and coefficients – thus none are included in the study.

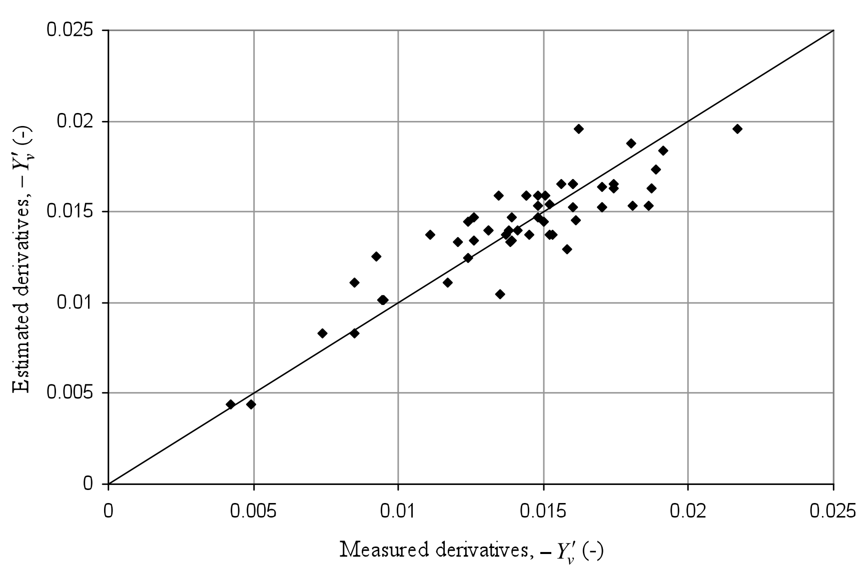


Fig. 5 – Evaluation of the Sway-force vs sway-velocity derivative estimate

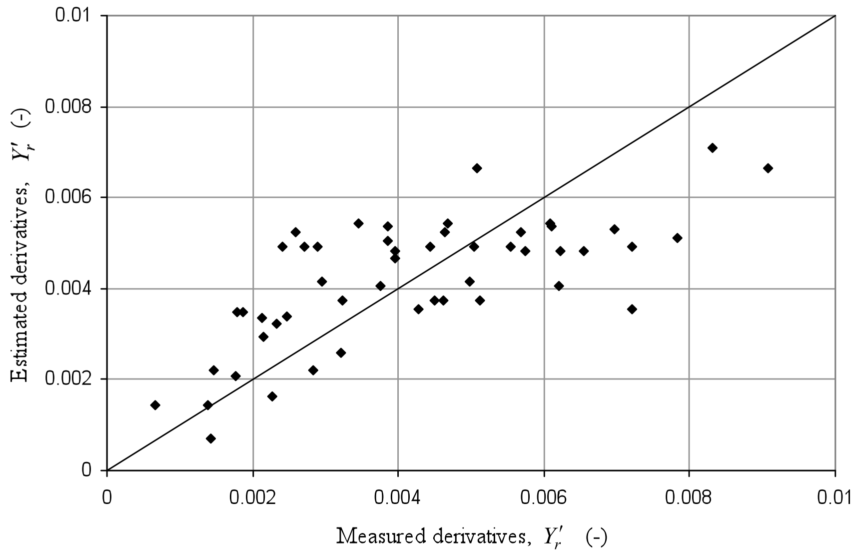


Fig. 6 – Evaluation of the Sway-force vs yaw-rate derivative estimate

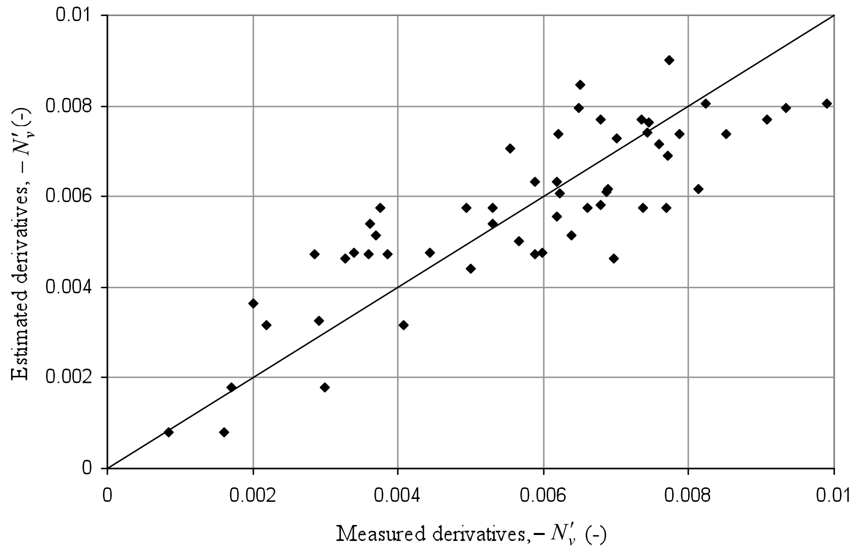


Fig. 7 – Evaluation of the Yaw-moment vs sway-velocity derivative estimate

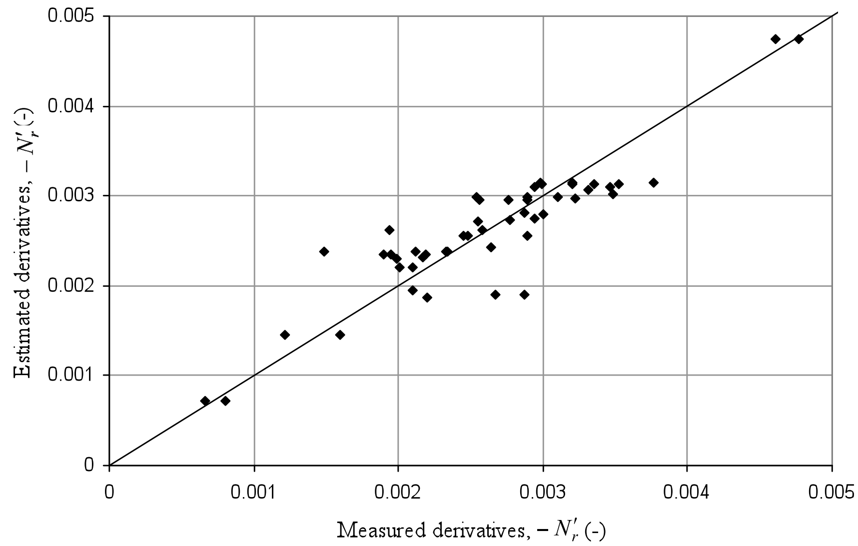


Fig. 8 – Evaluation of the Yaw-moment vs yaw-rate derivative estimate

4.2 Propeller

Perhaps the most obvious difference between an azimuthing pod drive and a conventional arrangement is that the propeller can now be placed at an angle of attack to the flow. The most predominant effect being that an individual propeller blade will now accelerate toward and away from the flow within one rotational cycle. To account for the relative inflow velocity Woodward et al. (2005) demonstrates that the relative advance angle is obtained as a function of blade position by Eq. 9, in terms for an effective advance velocity; re-derived in a similar form to those proposed by van Lammeren et. al. (1969).

The propeller can now be placed at an angle to the flow.

This means that its blades accelerate and decelerate w.r.t. the flow; for each cycle

$$\beta(\upsilon) = \arctan\left\{\frac{V_E \cos\delta_E}{0.7\pi nD + V_E \sin\delta_E \sin\upsilon}\right\} \qquad \text{Eq. 9}$$

Using a Fourier fit to represent this four-quadrant relative advance-angle curve, the thrust coefficient in terms of blade position is given by Eq. 10 and the torque coefficient in terms of blade position is given by Eq. 11.

$$C_T^*(\upsilon) = \sum_{K=0}^{m} \left\{A_T(K)\cos\left[K\,\beta(\upsilon)\right] + B_T(K)\sin\left[K\,\beta(\upsilon)\right]\right\} \qquad \text{Eq. 10}$$

$$C_Q^*(\upsilon) = \sum_{K=0}^{m} \left\{A_Q(K)\cos\left[K\,\beta(\upsilon)\right] + B_Q(K)\sin\left[K\,\beta(\upsilon)\right]\right\} \qquad \text{Eq. 11}$$

Then using these definitions, the thrust for any blade position is given by Eq. 12 and the torque for any blade position is given by Eq. 13.

$$\mathrm{T}(\upsilon) = \tfrac{1}{2}\rho\left[\left(V_E\cos\delta_E\right)^2 + \left(0.7\pi\,n\,D + V_E\sin\delta_E\sin\upsilon\right)^2\right]\tfrac{1}{4}\pi D^2 C_T^*(\upsilon) \qquad \text{Eq. 12}$$

$$Q(\upsilon) = \tfrac{1}{2}\rho\left[\left(V_E\cos\delta_E\right)^2 + \left(0.7\pi\,n\,D + V_E\sin\delta_E\sin\upsilon\right)^2\right]\tfrac{1}{4}\pi D^3 C_Q^*(\upsilon) \qquad \text{Eq. 13}$$

The total thrust, torque and propeller side force are obtained from integrating in terms of blade position by Eq. 14, Eq. 15 and Eq. 16 respectively.

$$\overline{\mathrm{T}} = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{T}(\upsilon)\,d\upsilon \qquad \text{Eq. 14}$$

$$\overline{Q} = \frac{1}{2\pi}\int_0^{2\pi} Q(\upsilon)\,d\upsilon \qquad \text{Eq. 15}$$

$$\overline{S} = \frac{1}{0.7D\pi}\left|\int_0^{\pi} Q(\upsilon)\,d\upsilon - \int_{\pi}^{2\pi} Q(\upsilon)\,d\upsilon\right| \qquad \text{Eq. 16}$$

Further, Woodward et al. (2005) demonstrates that the total change in force due to phase shift must, by definition, be zero but that the added-mass effects will contribute. Terms are given to approximate the propeller blade added-mass coefficients. The relative advance velocity is given by Eq. 17 and acceleration by Eq. 18.

So, these equations account for the change in inflow angle as the blade goes around.

$$V_R = \sqrt{\left(V_E \cos\delta_E\right)^2 + \left(0.7\pi nD + V_E \sin\delta_E \sin\upsilon\right)^2}$$ *Eq. 17*

$$\frac{\delta V_R}{\delta v} = \frac{V_E \sin\delta_E \cos\upsilon\left(0.7\pi nD + V_E \sin\delta_E \sin\upsilon\right)}{\sqrt{\left(V_E \cos\delta_E\right)^2 + \left(0.7\pi nD + V_E \sin\delta_E \sin\upsilon\right)}}$$ *Eq. 18*

And these equations account for blade acceleration as it goes around.

The total change in thrust due to the added-mass effects are given by Eq. 19 and the total change in torque due to the added-mass effects are given by Eq. 20; where A_{11} and A_{22} represent the added-mass coefficients on the propeller blade face and leading edge respectively.

$$\Delta T = \frac{\partial V_R}{\partial v}\left(A_{11}\sin\alpha\cos\phi - A_{22}\cos\alpha\sin\phi\right) z$$ *Eq. 19*

$$\Delta Q = \frac{\partial V_R}{\partial v}\left(A_{11}\sin\alpha\sin\phi + A_{22}\cos\alpha\cos\phi\right)\tfrac{1}{2}0.7Dz$$ *Eq. 20*

Using the above defined terms the total horizontal plane forces acting on the propeller are obtained as a function of the flow speed, the flow inclination angle and the propeller shaft rate.

4.3 Pod-body

The lift and drag characteristics of the nacelle and strut in combination are obtained according to Woodward et al. (2005). The model assumes a conventional lift curve slope in terms of effective aspect ratio given by Eq. 21.

$$\frac{\partial C_L}{\partial \delta_E} = \frac{2\pi}{1+\left(2/\sigma\right)}$$ *Eq. 21*

In addition, a method is given for approximating the effective aspect ratio in terms of the strut chord and span, the body radius, the ratio between the strut and body horizontal projected area (shown in Fig. 1) and the double body effect; given by Eq. 22

$$\sigma = \frac{k\, s_P}{c_P} + \frac{1}{c_P}\left(r_P - \frac{A_1}{A_2} r_P\right)$$ *Eq. 22*

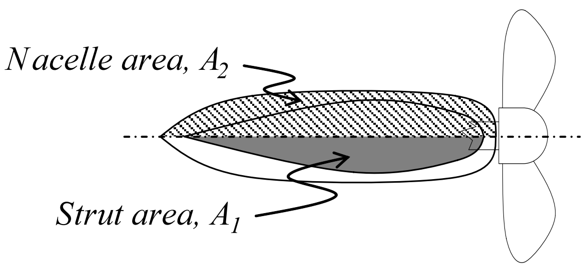


Fig. 9 – Ratio of nacelle and strut horizontal area

The pod-body blocks the flow around the bottom so the strut is more effective as a rudder.

The lift curve slope is used only for the first and last 20° of a half rotation of the pod; the interim period assuming only cross-flow-drag of the form $C_D \sin\delta_E$. To obtain a continuous function, a Fourier series transform is fitted to the 'piece-part' curve giving the lift coefficient curve $C_L^*(\delta_E)$, in terms of the Fourier coefficient terms $A_\delta(K)$ and $B_\delta(K)$; given by

$$C_L^*(\delta_E) = \sum_{K=0}^{m}\left[A_\delta(K)\cos(K\,\delta_E) + B_\delta(K)\sin(K\,\delta_E)\right]$$ *Eq. 23*

The effective velocity at the pod-body is obtained as a function of the inflow angle and the down-wash effect, by Eq. 24 with the angle given by Eq. 25.

$$V_S^2 = \left[V_E + aV_E\cos(\delta_E + \varpi)\right]^2 + \left[aV_E\sin(\delta_E + \varpi)\right]^2$$ *Eq. 24*

$$\gamma = \arctan\left[\frac{aV_E\sin(\delta_E + \varpi)}{V_E + aV_E\cos(\delta_E + \varpi)}\right]$$ *Eq. 25*

The velocity of the flow is obtained in terms of the axial flow factor a, given by Eq. 26; in terms of the race contraction factor K_M (here assumed to be unity), and the total mean force coefficient $\overline{C}_{TS}^*$, given by Eq. 27.

$$a = K_M\left(\sqrt{1 + \overline{C}_{\mathrm{TS}}^*} - 1\right)$$ *Eq. 26*

$$\overline{C}_{\mathrm{TS}}^* = \frac{\sqrt{\overline{\mathrm{T}}^2 + \overline{S}^2}}{\frac{1}{2}\rho V_E^2\,\frac{1}{4}\pi D^2}$$ *Eq. 27*

The axial flow angle ϖ, is found in terms of the propeller mean thrust and side force by Eq. 28 and combined as shown in Fig. 2.

$$\varpi = \arctan\left(\frac{\overline{S}}{\overline{\mathrm{T}}}\right)$$ *Eq. 28*

Then, the total mean lift-force is given by Eq. 29 in terms of the effective area and the lift coefficient curve.

$$\overline{L}_P = \tfrac{1}{2}\rho V_S^2\, s_P\, c_P\, C_L^*(\delta_E)(\delta_E - \gamma)$$ *Eq. 29*

Also, the profile drag-force is given by Eq. 30; in terms of the pod surface area and the ITTC (1957) frictional drag coefficient.

$$D_P = \tfrac{1}{2}\rho V_S^2\, s_P\, C_F\left(1 + k_{POD}\right)$$ *Eq. 30*

The effect of form-drag is accounted for by a 12% pod form-factor, k_{POD}. In fact, pod form-drag is proving to be a complex problem requiring further investigation however, the total effect of form-drag on this analysis is small; thus the approximation is considered satisfactory.

The propeller changes the flow; so these equations work out the effective helm angle.

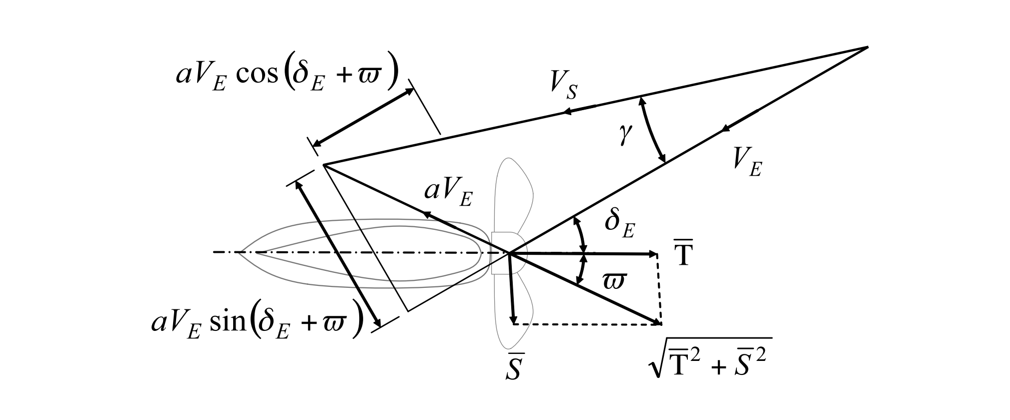


Fig. 10 – Flow velocity at pod-body

5 Numerical Simulation

The nature of the ship system is highly time-dependant. The loads on the pod are dependant on the ship velocity and the propeller rate of rotation. In turn, the ship velocity and propeller rate are dependant on the forces generated by the pods. The way these interdependent relationships develop with time and through specific manoeuvres cannot be predicted from the steady state analysis. Nevertheless, numerical solution to differential equations can be readily obtained and provide much insight into the true nature of time-dependant response.

5.1 Algorithm development

The study of time-domain simulation, to assess the manoeuvring performance of ship, is by no means a new idea. Generally speaking, the force derivatives are obtained from model testing and combined in a piece-part manner to obtain the overall response. Oltmann and Sharma (1984) provide a through account of a simulation methodology for conventionally propelled ships using force coefficients. Also, Ankudinov et al. (1993) provides account of a simulation methodology for conventionally propelled ships using approximation formula for the force coefficients.

After reviewing the options, the LabVIEW software was identified as the most suitable for the chosen application. And, for practicality, it was decided to modularise the work. That is, instead of creating one complete program, a suite of pod-driven ship simulation tools was developed as ‘plug-and-play’ sub-routines. In this way no decision had to be taken as to the future of the software or of pod-driven ship configurations. For example, if future applications need more pods or combinations of pods and other propulsion systems, the developed tools can then be assembled in the desired fashion. To this end, a time-domain simulation routine was developed and is designed to act as an operating environment for the derived sub-routines. The numerical methodology used for integration is the fourth-order Runge-Kutta method for differential equations; as described by Farlow (1994).

5.2 Ship dynamics

The horizontal plane lateral and rotational accelerations are calculated in terms of the lateral and rotational velocities. For the surge acceleration, the hull-form surge velocity derivatives are obtained from the coefficients of a least square fit of the resistance curve; itself obtained in terms of the hull-form principle dimensions and coefficients according to Holtrop and Mennen (1978). The surge acceleration is then obtained in terms of the surge velocity derivatives, the sum of the pod surge contributions and in terms of the approximated hull-form mass and added mass, by Eq. 31; where the surge added-mass is approximated by Eq. 32 - according to Oltmann [2003].

$$\dot{u} = \frac{X_{uuuu} u^4 + X_{uu} u^2 - \sum X_P^n}{m - X_{\dot{u}}} \qquad \text{Eq. 31}$$

$$X_{\dot{u}} = 0.11m - 0.228\, m C_B \qquad \text{Eq. 32}$$

Similarly, the sway acceleration is obtained in terms of the hull-form derivatives (described in the 'Hull-form' section above) and the sum of the pod sway force contributions, by Eq. 33.Likewise, the yaw acceleration is obtained in terms of the hull-form derivatives (described in the 'Hull-form' section above) and the sum of the pod yaw moment contributions, by Eq. 34.

$$\dot{v} = \frac{\left(I_Z - N_{\dot{r}}\right)\left(Y_v + Y_r\right) + Y_{\dot{r}}\left(N_r + N_v\right) - \sum Y_P^n}{\left(m - Y_{\dot{v}}\right)\left(I_Z - N_{\dot{r}}\right) - N_{\dot{v}} Y_{\dot{r}}} \qquad \text{Eq. 33}$$

$$\dot{r} = \frac{\left(m - Y_{\dot{v}}\right)\left(N_r + N_v\right) + N_{\dot{v}}\left(Y_v + Y_r\right) - \sum N_P^n}{\left(m - Y_{\dot{v}}\right)\left(I_Z - N_{\dot{r}}\right) - N_{\dot{v}} Y_{\dot{r}}} \qquad \text{Eq. 34}$$

The solutions for *u*, *v* and *r*, are obtained numerically using the fourth-order Runge-Kutta method for differential equations. Also, when it is necessary to know the position of the ship with respect to the global axis system, the horizontal displacement is obtained by direct integration.

So these equations give us the surge, sway and yaw accelerations.

5.3 Pod dynamics

To estimate the total forces acting on the pod the local velocities and accelerations are found in terms of the ship horizontal plane motions, the pod slew rate and the propeller shaft rate. Based on the ships horizontal plane motion and the pods location, and taking into account the helm angle, the local flow velocity is obtained. Then, based on the obtained effective angle-of-attack and the shaft-rate, the propeller thrust, torque and side force are calculated. Next, taking into account the global and propeller induced velocities the effective angle-of-attack at the pod-body is estimated and from that the lift-force due to the pod-body.

In the next step the propeller shaft rotational acceleration is obtained in terms of the mechanical efficiency (assumed to be 95%), the developed motor torque, itself a function of shaft rate, and control input by Eq. 35.

$$\ddot{\upsilon} = \frac{\eta_M Q_M(\dot{\upsilon}, C) - Q(\dot{\upsilon})}{2\pi I_{\upsilon}}$$ *Eq. 35*

The experienced torque is obtained as a function of shaft rate and the system moment of inertia; approximated from the geometry of the full-scale motor including the motor, the shaft and the propeller contribution. Again, the solution for $\dot{\upsilon}$, is obtained numerically using the fourth-order Runge-Kutta method for differential equations. The breaking effect of the electric motor, defining the developed torque, is given by Eq. 36; including a control input (between -1 and 1) and a non-dimensional shaft rate forming a linear surface, with coefficient terms d_Q and e_Q defining the surface gradients – the coefficient terms are selected to suit the performance characteristics of the motors in use.

$$Q_M(\dot{\upsilon}, C) = d_Q C + e_Q \frac{\dot{\upsilon}}{\dot{\upsilon}_{MAX}}$$ *Eq. 36*

In the next step, the stock shaft rotation acceleration is obtained in terms of the slewing mechanical efficiency (assumed to be 95%); the applied slewing torque; the slewing rate; the pod-body lift force and its lever about the slewing stock; the propeller side force and its lever about the slewing stock; the pod mass moment of inertia; given by Eq. 37.

$$\ddot{\delta}_P = \frac{\eta_\delta Q_\delta - \dot{\delta}_P P_{\dot{\delta}} - \overline{L}_P l_L - \overline{S} l_S}{I_\delta + P_{\ddot{\delta}}}$$ *Eq. 37*

Both the pod-damping coefficient, given by Eq. 38 and the added-mass moment of inertia, given by Eq. 39 are approximated for the form of a flat plate with the same span, and chord, as the pod-body; in accordance with Jones [1946].

$$P_{\dot{\delta}} = \tfrac{1}{4}\pi\left(\frac{s_P}{c_P}\right)^2 \tfrac{1}{2}\rho U_o^2 c_P^4$$ *Eq. 38*

$$P_{\ddot{\delta}} = \tfrac{1}{12}\pi\left(\frac{s_P}{c_P}\right)^2 \tfrac{1}{2}\rho c_P^5$$ *Eq. 39*

The solution for $\dot{\delta}_P$, is obtained numerically using the fourth-order Runge-Kutta method for differential equations and by direct integration. For the response analysis it is sufficient that the slewing motor torque is selected so as to provide the same slewing rate as in the model tests. The specific value of torque is however highly sensitive to the lever terms and the output is vital for the structural design; investigated in more detail by Woodward et. al. (2005a). Also, the added-mass associated with the pod accelerating sideways due to ship yawing or swaying is accounted for by Eq. 40 where C_H is the section added-mass; given in Fig. 11 according to Clarke [1976].

$$P_{\dot{v}} = -\pi\left(\frac{s_P}{c_P}\right)^2 \int_0^{c_P} C_H x' dx'$$ *Eq. 40*

Then, by fitting a polynomial to the curve given in Fig. 10 and assuming that the cross-section is constant along the length of the pod-body, we obtain the total pod sway added-mass in terms of the pod-body span, chord, and the nacelle radius, from Eq. 41.

$$C_H = \tfrac{1}{2}\rho c_P^3 \left\{ 1 - 3.17\left[\frac{r_P}{s_p + r_P}\right]^2 + 1.86\left[\frac{r_P}{s_p + r_P}\right] \right\}$$ *Eq. 41*

For the above calculations the mass moments of inertia are approximated about the slewing stock by Eq. 42 and about the propeller shaft by Eq. 43.

$$I_\delta \approx \tfrac{1}{12}\pi r_P^2 c_P \rho_P \left(3 r_P^2 + c_P\right)$$ *Eq. 42*

$$I_p \approx \tfrac{1}{2}\pi r_P^4 c_P \rho_P$$ *Eq. 43*

The shaft inertia is assumed to be the sum of the motor, the propeller shaft and the propeller contributions and in all cases the pod density is approximated at 6000 kg/m^3. Finally, the slewing control of the pod is executed using a simple PID controller; assuming the conventional transfer function given by Eq. 44 in terms of the Laplace operator *s*, and the three coefficients; proportional gain, integral gain, derivative gain – selected to suit each ship type.

$$G_c(s) = K_1 + \frac{K_2}{s} + K_3 s$$ *Eq. 44*

In order to complement the algorithm development a simple flowchart is provided in Fig. 12; demonstrating the simulation process and implementing the above formulations.

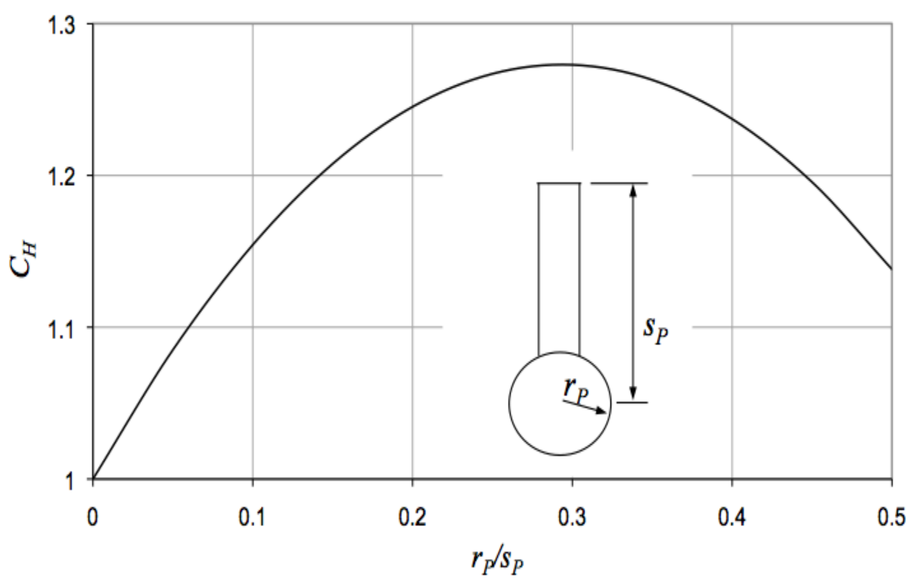
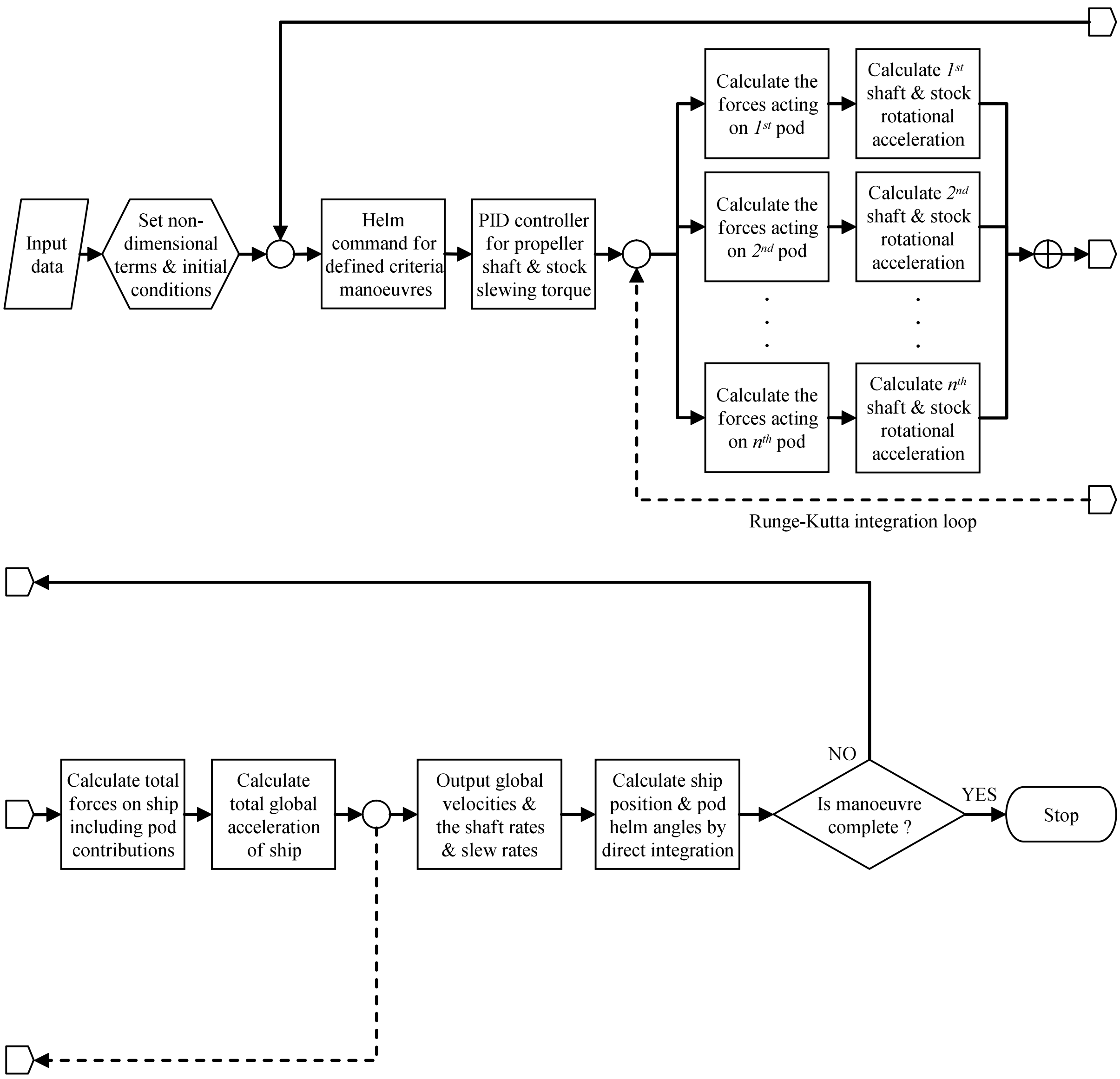


Fig. 11 – Estimation of pod added-mass in sway direction

Fig. 12 – Flowchart of simulation process



5.4 Validation of simulation model

To validate the simulation tools, predicted results are compared to the results of free-running model tests. Three representative ship types are selected as typical of current pod-driven ship designs: a Cargo ship; a Ropax; a Cruise ship.

Simulations are compared with free-running tests; like those we saw in Poland!

The Cargo ship is propelled by a single puller-type pod and the Ropax and Cruise ship by twin puller-type pods; general particulars of the three ships are given in Table 1 and each body-plan and isometric view is given in Fig. 13, Fig. 14 and Fig. 15 respectively.

For the Cargo ship model, a comparison of the 20/20 zig-zag manoeuvre conducted at an equivalent ship speed of 15 knots is given in Fig. 16. Though the magnitude of the first overshoot is underestimated, the general behaviour of the response is modelled well.

A comparison of the ship's speeds, while performing this 20/20 zig-zag manoeuvre is given in Fig. 17; the measured and simulated values compare very well.

Next, Fig. 18 compares the unit-thrust force (x-axis in the ship fixed coordinate system) for the 20/20 zig-zag manoeuvre. In general, the magnitude is well predicted and most notably, the peak loads associated with dynamic effect are modelled very well. Likewise, Fig. 19 compares the unit-control force (y-axis in the ship fixed coordinate system) for the 20/20 zig-zag manoeuvre. And again, the magnitude is well predicted and most notably, the peak loads associated with dynamic effect are apparent.

For the Ropax model, a comparison of the 10/10 zig-zag manoeuvre conducted at an equivalent ship speed of 28 knots is given in Fig. 20; demonstrating excellent results. A comparison of the 20/20 zig-zag manoeuvre conducted at an equivalent ship speed of 28 knots is given in Fig. 21; also demonstrating excellent results.

Figure 22 gives a comparison of the measured and estimated unit-control force during the application of a 35^{o} helm angle. Clearly, the force for the steady state turning motion is very well estimated. Perhaps more interestingly, the behaviour associated with dynamic slewing is approximated well by the simulation model. The same type of result can be observed in Fig. 23; but this time for a 5/5 zig-zag manoeuvre. The appearance of a spiked response for dynamic slewing is clearly apparent and is modelled well by the simulation.

Comparison of the turning circle advance for various applied helm angles is given in; Fig. 24 tested at 28 knots equivalent. In each case the maximum and minimum test results are shown together with the simulated predictions. Some overestimate is apparent and more pronounced at smaller helm angles. However, good comparison is observed for the general trend.

Comparison of the turning circle tactical diameter for various applied helm angles is given in Fig. 25; tested at 28 knots equivalent. And again, good comparison can be observed for the general trends though overestimate is apparent; and more pronounced at smaller helm angles.

Table 1 – OPTIPOD ship particulars

Parameter		Cargo	Ropax	Cruise
Scaling ratio	λ (-)	27.5	23.0	25.1
Length	L (m)	155.0	194.0	274.1
Breadth	B (m)	27.0	28.4	32.2
Draught	T (m)	8.5	6.6	8.0
Block Coefficient	C_B (-)	0.765	0.613	0.646
Aft-body shape parameter	σ_a (-)	0.240	0.199	0.200
Propeller diameter	D (m)	4.95	5.30	5.75
Propeller pitch-diameter ratio	P/D (-)	0.791	1.389	1.005
Propeller blade-area ratio	A_E/A_0 (-)	0.600	0.758	0.753
Number of propeller blades	ζ (-)	4	4	4
Pod lateral area	A_P (m^2)	17.80	23.30	39.80
Pod strut chord	c_P (m)	4.01	6.20	6.00
Pod strut span	s_P (m)	5.00	3.30	5.80
Pod nacelle radius	r_P (m)	1.30	1.32	1.71
Pod-strut horizontal area ratio	A_1/A_2 (-)	0.31	0.35	0.28
Double body coefficient	k(-)	2	2	2
Number and type of pods	Pods	1 x puller	2 x puller	2 x puller

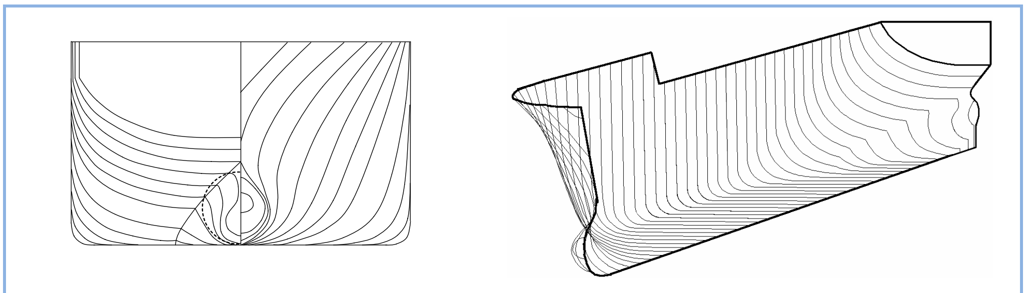


Fig. 13 – Drawings of the OPTIPOD Cargo ship

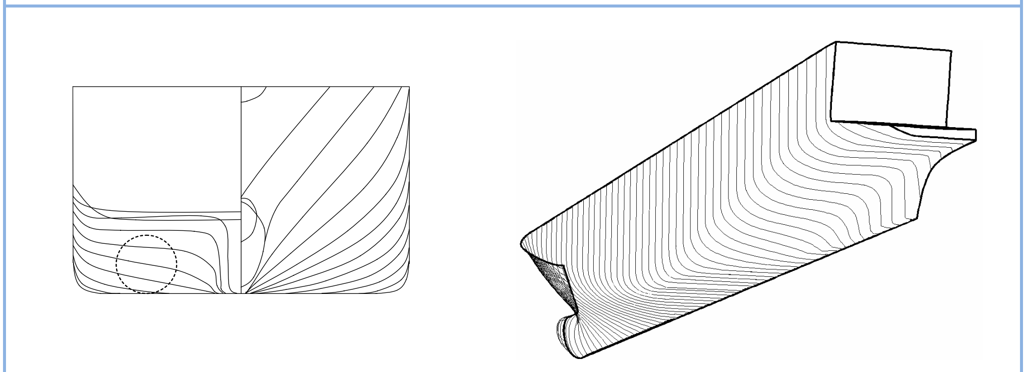


Fig. 14 – Drawings of the OPTIPOD Ropax

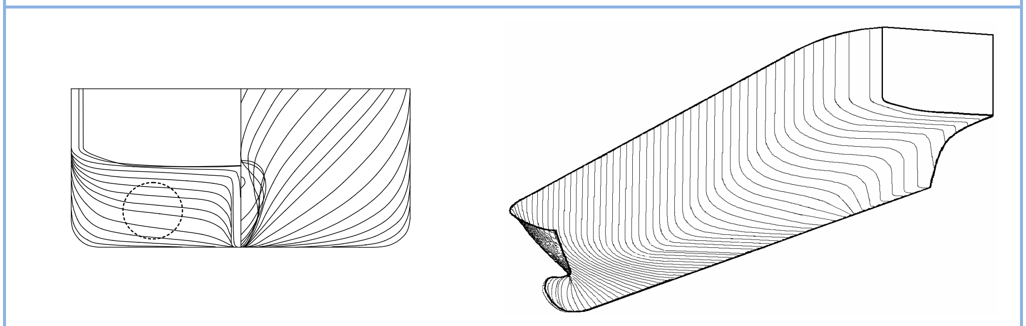


Fig. 15 – Drawings of the OPTIPOD Cruise ship

For the Cruise ship model, a comparison of the 10/10 zig-zag manoeuvre conducted at an equivalent ship speed of 21.9 knots is given in Fig. 26. The results show excellent comparison, presenting very similar overshoot values. Finally, a comparison of the 10/10 zig-zag manoeuvre conducted at an equivalent ship speed of 16 knots is given in Fig. 27 – again good results are observed.

For clarity, comparisons of the overshoot-angles and switch-times for the test results and simulated values are given in Table 2.

Ship Type	Test Type	Relative Speed	First Overshoot *(Test/Sim)*	Second Overshoot *(Test/Sim)*	First Switch *(Test/Sim)*	Second Switch *(Test/Sim)*
Cruise	10/10	100%	$6^o/5^o$	$7^o/6^o$	7s/7s	25s/24s
Cruise	10/10	73%	$4^o/3^o$	$7^o/4^o$	12s/9s	33s/32s
Ropax	10/10	100%	$4^o/4^o$	$6^o/4^o$	3s/4s	12s/13s
Ropax	20/20	100%	$9^o/10^o$	$7^o/8^o$	3s/3s	14s/12s
Cargo	20/20	100%	$21^o/15^o$	$25^o/24^o$	30s/33s	117s/126s

Table 2 – Comparison of test results and simulation values

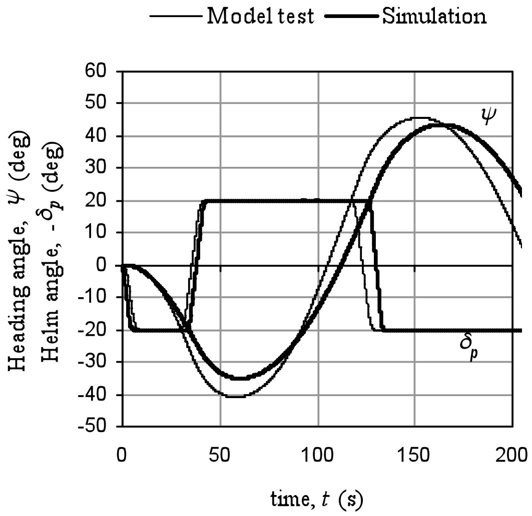


Fig. 16 – Cargo ship zig-zag test; Heading

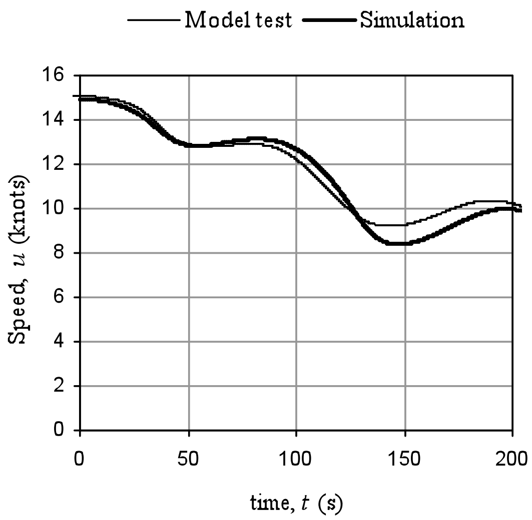


Fig. 17 – Cargo ship zig-zag test; Unit-control force

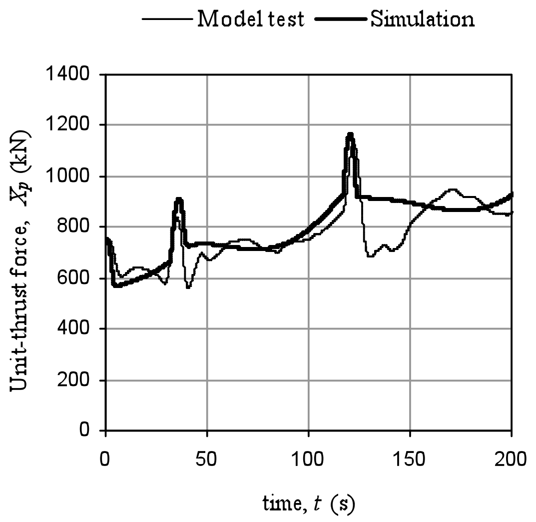


Fig. 18 – Cargo ship zig-zag test; Unit-thrust force

Note the spikes; they occur when we slew the pod!

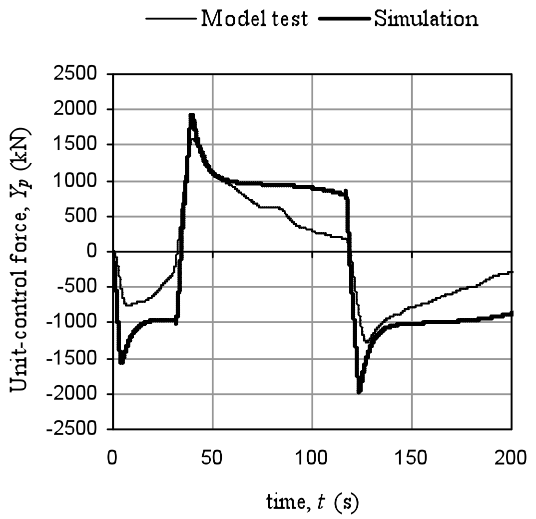


Fig. 19 – Cargo ship zig-zag test; Unit-control force

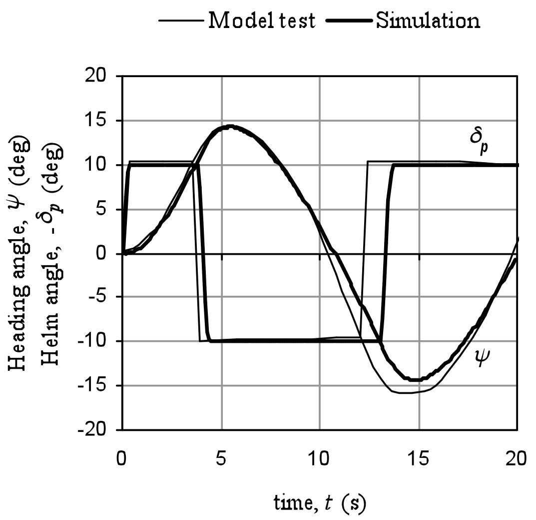


Fig. 20 – Ropax 10/10 zig-zag test; Heading

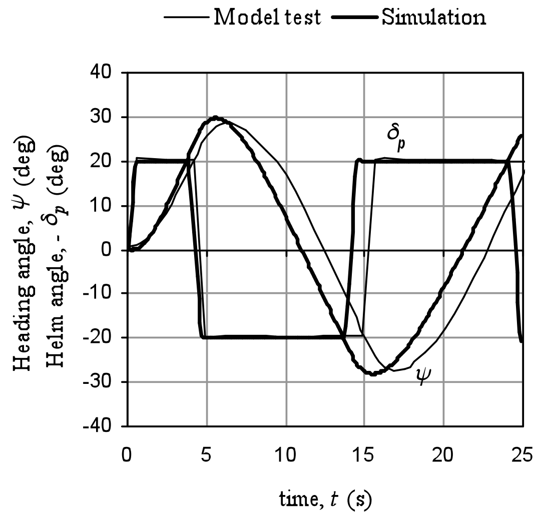


Fig. 21 – Ropax 20/20 zig-zag test; Heading

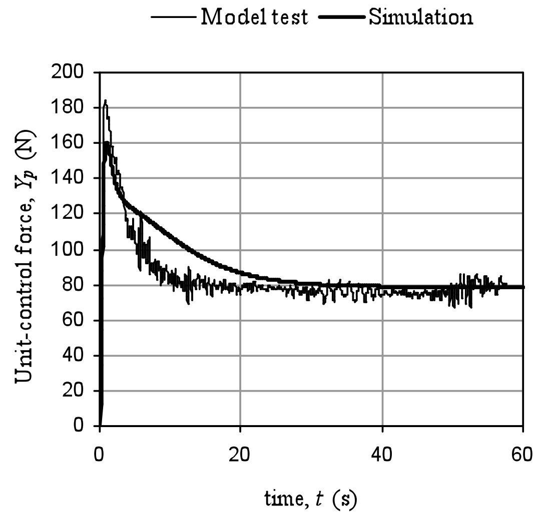


Fig. 22 – Ropax Turning Circle; Control force

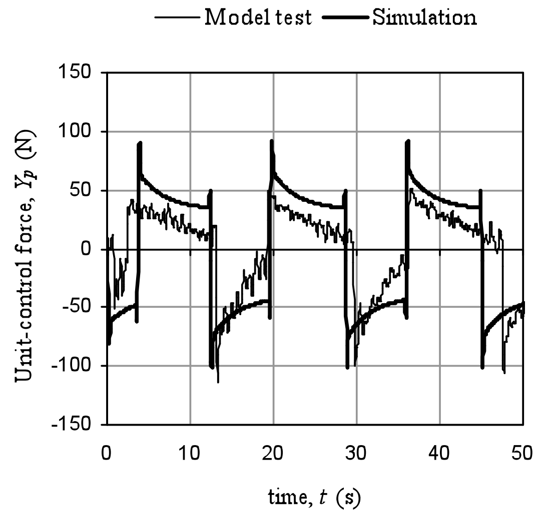


Fig. 23 – Ropax Zig-zag; Control force

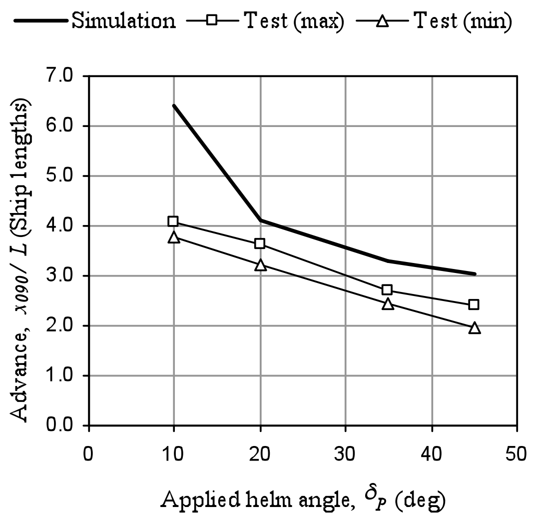


Fig. 24 – Ropax Turning Circle; Advance

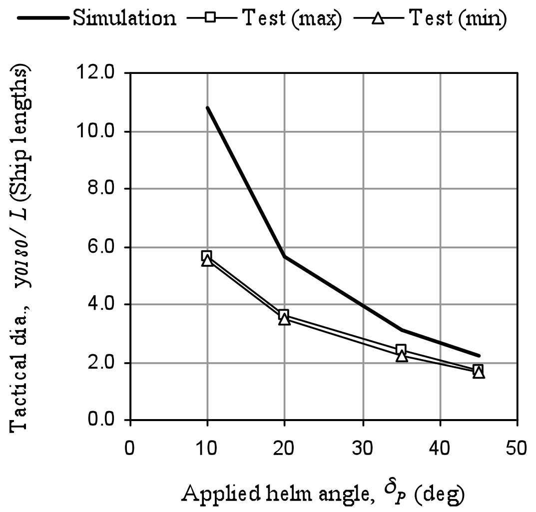


Fig. 25 – Ropax Turning Circle; Tactical diameter

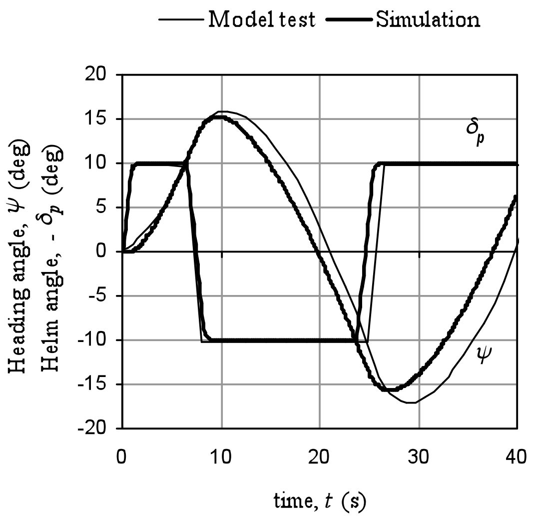


Fig. 26 – Cruise zig-zag @ 22 kn; Heading

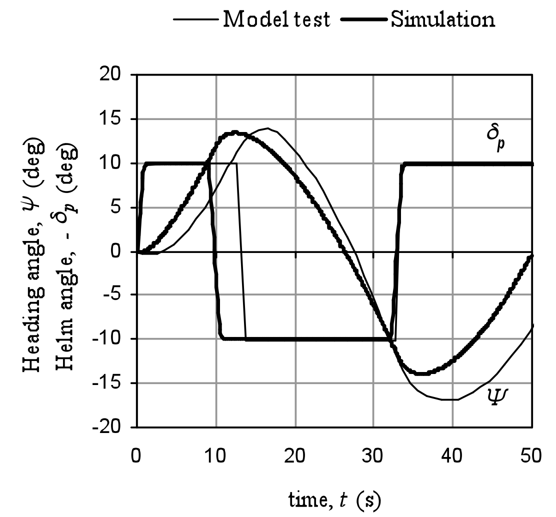


Fig. 27 – Cruise zig-zag @ 16 kn; Heading

5.5 Parametric evaluation of criteria

The sea can be a very unforgiving environment and the evolution of sea transport has not been without cost. From around the 1850's the first treaties were made by the international community to improve the safety of persons and property in the marine environment. The most significant advancement came with the formation of the United Nations (UN) with, in 1948, the formation of the IMCO; entering into force in 1958 (renamed IMO in 1982). The main purpose of the International Maritime Organisation (IMO) is to facilitate cooperation between governments to encourage the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships.

The interim standards for ship manoeuvrability were first introduced in 1993 in an attempt to improve maritime safety and enhance marine environmental protection. The aim of the standards is to improve ship performance with the objective of avoiding the building of ships that do not comply with the criteria. The objective of the work herein is to make qualified assessment of the validity of the IMO manoeuvring criteria 'Resolution MSC.137(76)', when applied to pod-driven ships.

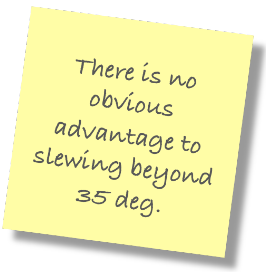
5.5.1 Turning Circle Criterion

To evaluate the turning behaviour of pod-driven ships, manoeuvring simulations are made with the three ships described above. There is little reason to question the suitability of the 4.5 ship length advance or the 5 ship length tactical diameter criteria. After all, these provide a perfectly good benchmark with which to measure the performance of all ships; regardless of propulsion type. However, the application of specific helm angle is much less clear – it may be necessary to use different helm angles or even a completely different approach.

The advance for a range of applied helm angles is given, for each ship, in Fig. 28. The curves for both the Ropax and the Cruise ship demonstrate the intuitive relationship. That is to say that, larger applied helm angle result in smaller advance values. Also, it is observed that the relationship is much more pronounced below applied helm angles of about 20°. In the region above 20° both the Ropax and the Cruise ship demonstrate a lesser but approximately linear decrease in advance for increased applied helm angle.

Perhaps somewhat less intuitive, the advance of the Cargo ship, demonstrates a more complicated behaviour. The region to the left of 20° applied helm angle still demonstrates the expected tendency. However, in the region to the right of 20°, an increase in the advance is observed before again reducing. This is somewhat easier to interpret when taking into account the fact that the Cargo ships forward speed was completely lost for tests using helm angles in excess of 20°; see Fig. 29. In fact, at higher applied helm angles the ship rapidly loses forward motion and the majority of the manoeuvre consists of purely sway and yaw motion.

Next, the tactical diameter for a range of applied helm angles is given, for each ship, in Fig. 30. It is observed that all three ships demonstrate the expected relationship; having a reduction in advance for increased applied helm angle. Again, the region to the left of 20° applied helm angle shows a stronger dependency. And again, the region to the right of the 20° applied helm angle demonstrated a lesser and more linear dependency. It is further observed that all three ships comply to both the advance and the tactical diameter criteria when a 35° helm angle is applied.



Overall, the observed turning behaviour presents no unexpected characteristics; showing a progressive reduction in the turning parameters for increased helm angle. In all cases the 35° applied helm angle gives a perfectly adequate benchmark for evaluating performance.

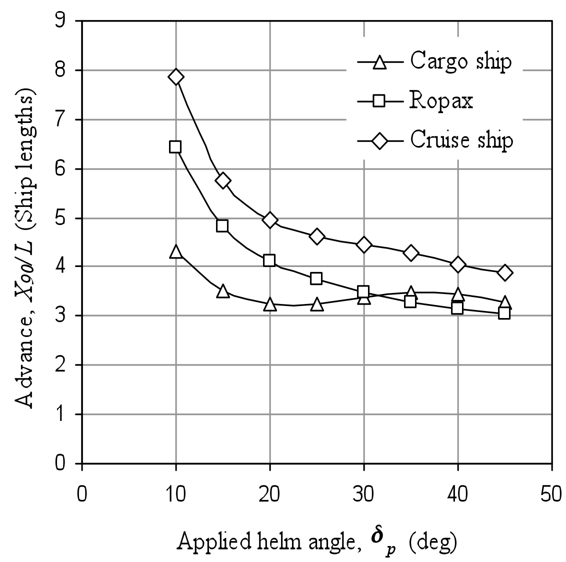


Fig. 28 – Turning circle test; Advance

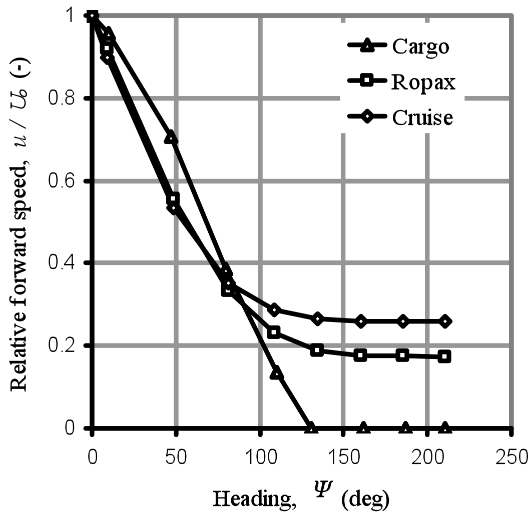


Fig. 29 – Speed loss in turn; 35 deg helm

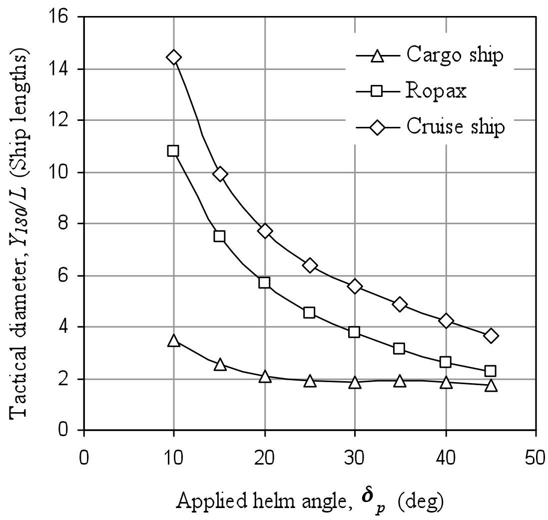


Fig. 30 – Turning circle test; Tactical diameter

5.5.2 Initial Turning Criterion

To evaluate the initial turning behaviour of pod-driven ships, manoeuvring simulations are made with the three ships described above. As with the turning tests, there is little reason to question the suitability of the criteria of 2.5 ship length within 10^{o} heading change. As before, this provides a perfectly good benchmark with which to measure the performance. But again, the application of specific helm angle is much less clear.

Figure 31 gives the initial turning in ship lengths against various applied helm angles for the Cargo ship. Further, the plot gives comparison of different pod slewing rates. The general trend of the curves is as expected; showing a reduction in initial turning distance with increased applied helm angle. On examination, it is clear that the region to the left of 10^{o} applied helm angle has a much more pronounced relationship. Conversely, the region to the right demonstrates only small changes in the initial turning distance for increased applied helm angle. However, when increasing the applied helm angle much above 10°, the effect of slew rate becomes fare more influential.

Figures 32 and 33 give the initial turning in ship lengths against various applied helm angles for the Ropax and Cruise ship respectively. Again, the plots give comparison of different pod slewing rates. And as with the Cargo ship, both plots demonstrate the same characteristics. The region to the left of 10° has most dependants on the applied helm angle; the region to the right of the 10° applied helm angle has most dependants on the slew rate.

10 deg. Helm seems to be a good compromise.

In all three cases the ships meet the initial turning ability criterion with the recommended 10° applied helm angle. And, in all three cases, the 10° applied helm angle give a good approximation of the mid-point between the two contributing influences (applied helm angle and pod slew rate). Overall, the behaviour presents no undue characteristics and in all cases the 10° applied helm angle gives a perfectly adequate benchmark for evaluating performance.

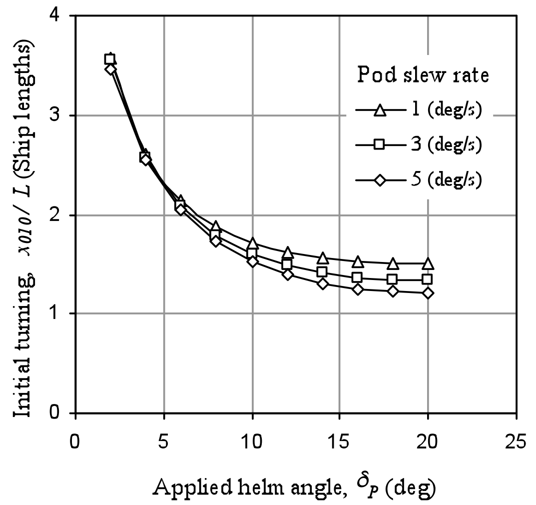


Fig. 31 – Initial turning test for the Cargo ship design

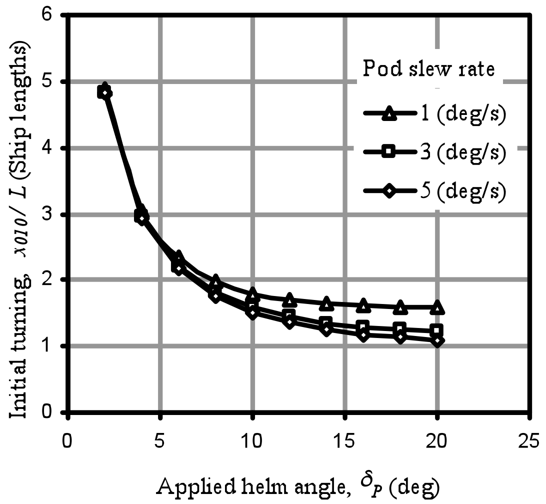


Fig. 32 – Initial turning test for the Ropax design

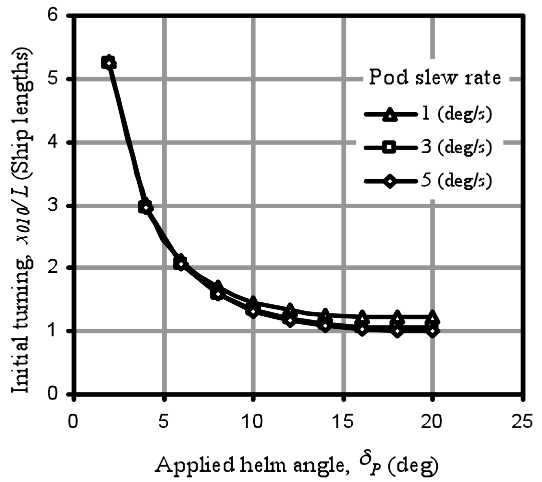


Fig. 33 – Initial turning test for the Cruise ship design

5.5.3 Yaw Checking Criterion

To better understand the yaw-checking criterion for pod-driven ships, criteria maps are developed as described by Clarke and Yap (2001). These criteria maps present some interesting non-linear behaviour that is as yet not fully explored. Nevertheless, they are ideal in this situation for making comparison between frequency- and time-domain behaviour. The simulation tool is used to calculate the criteria parameters together with a range of open-loop phase angles in an attempt to draw comparison between the two. Clarke (1992) argues that the helmsman should be capable of introducing some 20^o of Phase and 12dB of Gain. Further, Nobukawa et al. (1990) argues that, even if the helmsman were receiving verbal commands from a pilot, it would still be possible to introduce some 5o of Phase and 12dB of Gain. Using the latter as guideline we would expect to observe the IMO criteria preventing the design of ships with less than -5^o Phase.

The criteria map for the Cargo ship is given in Fig. 34. The vertical axis describes a proportional change in the control derivative which is introduced by adjusting the pod-body lateral area. The horizontal axis describes a proportional change in the hull-form derivative which is achieved by introducing a fictitious fin at the stern of the ship. The centre of the plot marks the performance point of the current design condition. All criteria limits are indicated by the darker lines (as marked) with the regions that fall outside the limits shaded in grey. Also, lines of constant Phase-margin are given; with magnitude as marked. The results show that the Cargo ship fails on both the 1st 20/20 and the 2nd 10/10 zig-zag criteria. It is apparent from the map that some 10% increase in the hull-form derivative is necessary to bring the design into the feasible region. What is perhaps of far more interest is the relationship between the lines of constant overshoot and the lines of constant Phase-margin. Both sets of lines can be seen to follow very similar contours, with the 1st 20/20 line and the 2nd 10/10 between the 0^o and -5^o Phase-margin lines.

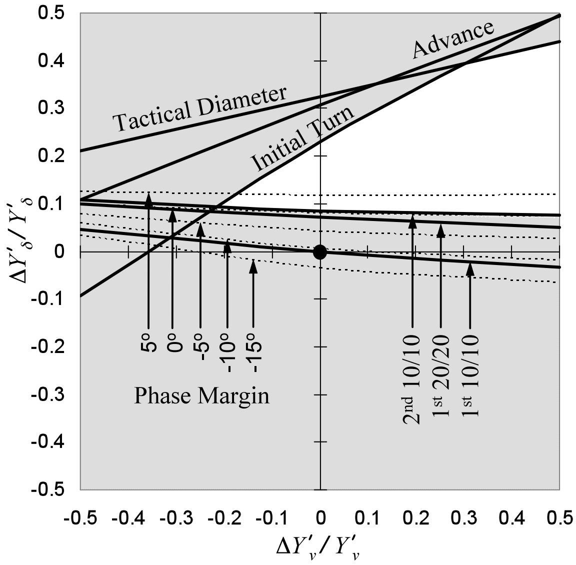


Fig. 34 – Criteria-map for the Cargo ship design

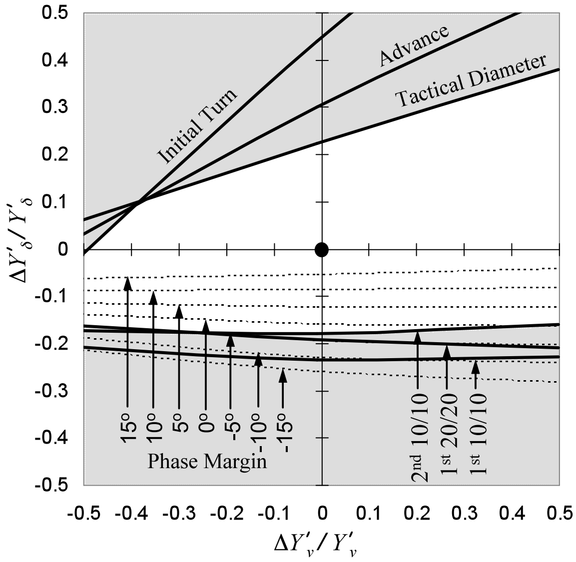


Fig. 35 – Criteria-map for the Ropax design

It appears that the current criteria approximate the phase angle well.

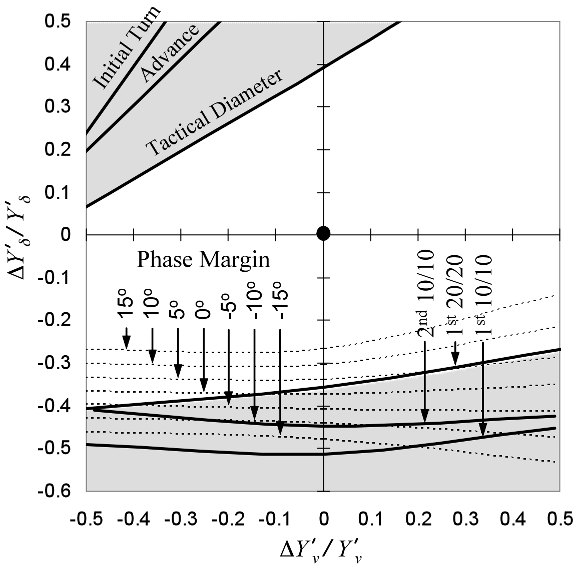


Fig. 36 – Criteria-map for the Cruise ship design

The criteria map for the Ropax is given in Fig. 35; where the presentation is as described above. The design map indicates that the Ropax has favourable manoeuvring performance characteristic; with the design point situated well within the feasible region. Again, what is of far more interest is the relationship between the lines of constant overshoot and the lines of constant Phase-margin. To the left of the figure the line of constant 1^{st} 20/20 limits the design; and is virtually concurrent with the line of constant -5^{o} Phase-margin. To the right of the figure the line of constant 2nd 10/10 overshoot is the limiting factor; and is situated between 0^{o} and -5^{o} Phase-margin.

The criteria map for the Cruise ship is given in Fig. 36; where again the presentation is as described above. The design map indicates that the Cruise ship has favourable manoeuvring performance characteristic; with the design point situated well within the feasible region. On investigation it is clear that the line of constant 1^{st} 20/20 limits the design and is situated between the lines of 5^{o} and -5^{o} Phase-margin.

5.5.4 Stopping Criterion

The criterion for ship stopping requires that a fully loaded ship in deep water, put full-astern from test speed, should achieve a track reach not exceeding 15 ship lengths. The criterion has also a provision for large displacement ships unable to comply where the value may be modified at the discretion of the Administration; but in no case should exceed 20 ship lengths.

To examine the effect on stopping behaviour a study was made using the Ropax as basis; reported in Woodward et al. (2005). For comparison, four stopping manoeuvres are chosen for simulation. In all cases the initial condition is at test speed (28.4 knots), on a straight heading and with a zero helm angle. And in all cases, the stopping distance is taken as the track distance covered until dead stop is achieved. First, a conventional stopping manoeuvre (CSM) is performed by ordering full-astern. Second, a 180^{o} slew stopping manoeuvre (SSM1) is performed by ordering the helm to 180^{o}, turning the pods outwards in opposite directions. Third, a 180^{o} slew stopping manoeuvre (SSM2) is performed by ordering the helm to 180^{o}, turning the pods outwards in opposite directions, while simultaneously ordering a 40% reduction in delivered shaft torque. Fourth, an indirect stopping manoeuvre (ISM) is performed by ordering the helm to 60^{o}, turning the pods outwards in opposite directions, while simultaneously ordering full-astern – when the ship speed has reduced by 80%, ordering the helm back to 0^{o}.

As reversing the rpm is the worst case, then we use it as a criteria with confidence.

Table 3 – Comparison of stopping manoeuvres

	Stopping distance (Ship lengths)	Stopping time (sec)
Conventional stopping manoeuvre (CSM)	11.97	303
Slew stopping manoeuvre 1 (SSM1)	6.66	201
Slew stopping manoeuvre 2 (SSM2)	9.05	299
Indirect stopping manoeuvre (ISM)	5.81	182

Table 3 compares the stopping distances and times for the described stopping manoeuvres. It is clear that the proposed alternative stopping manoeuvres can stop the ship sooner; and perhaps with more control. However, it is also apparent that the conventional method of stopping is still perfectly applicable and directly equivalent to conventionally propelled ships.

5.6 Discussion of the implications for manoeuvring criteria

The turning ability criteria are evaluated using systematic simulation of manoeuvres. For each of the three ships the advance and tactical diameter criteria are investigated for a range of applied helm angles. In each case it is clear that the turning parameters reduce with increased applied helm angle. The advance of the Cargo ship shows some increase between the 20° and 35° applied helm angle however, no specific risk of collision is relevant as all forward speed is lost. In all cases the turning parameters increase rapidly with reduced applied helm angle. And in all cases, there is little to be gained for applied helm angle above 35°. All test results indicate that a 35° applied helm angle is entirely appropriate for testing the turning ability of pod-driven ships.

The initial turning ability criterion is evaluated using systematic simulation of manoeuvres. For each of the three ships the initial turning for various applied helm angles and for different pod-slewing rates is calculated. All cases demonstrate reduced advance for increased applied helm angle; showing a significantly more pronounced relationship for applied helm angles of less than 10°. Also, all cases demonstrate increased variation with respect to slew rate for applied helm angles above 10°. All test results indicate that a 10° applied helm angle is entirely appropriate for testing the initial turning ability of pod-driven ships.

The yaw-checking criteria are evaluated using systematic simulation of manoeuvres. IMO criteria-maps are used to compare lines of constant criteria values with lines of constant Phase-margin. In all cases it is observed that the lines of constant Phase-margin and the lines of constant IMO overshoot criteria follow very similar contours. All test results indicate that the 10/10 and 20/20 test criteria are entirely appropriate for testing the yaw-checking ability of pod-driven ships as they approximate well the -5° Phase-margin.

The stopping ability criterion is evaluated using systematic simulation of manoeuvres. The stopping criterion is investigated together with other methods of stopping pod-driven ships. The study finds that other options exist that can stop a pod-driven ship more efficiently and perhaps with less loading on the propeller. The study finds that the conventional stopping method (reversal of rpm) is the least effective at stopping the ship. Thus, it is appropriate as a benchmark to prevent the building of ships that do not meet the criterion. Therefore, the existing criterion is entirely appropriate for testing the stopping ability of pod-driven ships.

Experimental test uncertainty was not calculated for the free-running model tests as the trends rather than specific values were being considered. Nevertheless, all efforts were made to ensure that the tests were conducted in accordance with normal testing procedures. Scaling error can be a problem for this type of testing but such effects were avoided by simulating like-for-like at the same scale. The sensitivity of the results for the simulated values were investigated and reported in Woodward et. al. (2005a).

Based on the assumptions made and the ship types used within this study, it is concluded 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.

Go ahead and use the current criteria for pod-driven ships..

Manoeuvring Induced Loading

One of the key claims for the azimuthing pod is that they provide 'improved manoeuvrability' – yet little has been done to quantify or substantiate this claim. The ability to maintain a steering control force even at zero speed does indeed provide significant advantages. However, the full implications of using a heavy and spinning motor to steer the ship are not well defined. Clearly, a better understanding of the dynamic system characteristics must be obtained if we are to limit the technological risk.

This section looks in more detail at the spike loads that we found in the last section.

6 Technical overview

As discussed in the previous section, a conventional rudder cannot be turned beyond 35° to 40° because flow separation will occur at higher angles and no further control force will be achieved. However, a pod-drive can be turned to any angle with no defined angle of maximum control force. Similarly, the acceleration related forces induced when slewing a 50 tonne rudder are vastly different from those for a 500 tonne pod drive. Further, the gyroscopic inertia induced by the spinning pod motor significantly modifies the total reaction. In fact, slew rate requirements for conventional rudders originate historically from a measure of the steering gear capacity and not from any concern about the dynamic loads. Clearly, applying similar slewing requirements to pod drives is wholly inappropriate.

6.1 Model testing

The work presented herein was conducted in both OPTIPOD and FASTPOD. OPTIPOD investigated all areas of pod-driven ship design using, among other ship types, the OPTIPOD Ropax to investigate the manoeuvring response. This was achieved through a comprehensive study including captive testing, numerical simulation and free-running testing. Also, FASTPOD, continuing from the OPTIPOD work, investigates the maximum feasible limit of pod technology when applied to fast ships. Again amongst others, the FASTPOD Ropax was used for a comprehensive model testing and simulation study to evaluate the manoeuvring performance of fast pod-driven ships. In both cases the investigations identify significant manoeuvring induced loads on the pods and in both cases these loads are predicted through the numerical simulations.

6.1.1 The OPTIPOD Ropax

The OPTIPOD Ropax has a length between perpendiculars of 172.2m, beam 28.4m, draught 6.6 m and displaces 19946 tonne. The ship is propelled by two puller-type pod-units both equipped with 5.3m propellers. Each pod absorbs approximately 20MW power and is fully azimuthing for ship manoeuvring control. A stern view of the OPTIPOD Ropax model is given in Fig. 37.

Free-running model tests were carried out for the OPTIPOD Ropax by CTO in Poland. The tests were conducted on Lake Wdzydze using an 8.5 m model equipped with two active azimuthing pod units. The pod propellers were driven mechanically from inside the hull and assume a constant torque model. The model was balanced both statically and dynamically in accordance with the design. In all tests the ships mid-point was recorded using GPS and the helm-angle, heading-angle and other parameters were recorded using a data recording computer system.

The tests considered all the IMO criteria manoeuvres measuring both ship response and induced pod loading. And, the side loading on the pod slewing stock provided some very interesting results. The steady state loading are roughly in line with what can be expected for a lifting surface experiencing an accelerated flow and including a thrust contribution. However, the loading experienced during the period of dynamic slewing presented a much higher value. In fact, in many cases, these spike-loads were in excess of twice the steady state loading. Figure 40 presents the model tests results (in model scale) for pod side loading when executing a 5/5 zig-zag manoeuvre and Fig. 6 for the case of a 35^0 applied helm-angle. In both cases the above described spike-loads can be clearly observed.

Fig. 37 – OPTIPOD Ropax

6.1.2 The FASTPOD Ropax

The FASTPOD Ropax has a length between perpendiculars of 228 m, beam 29.3 m, draught 6.5 m and displaces 16719 tonne. The ship is propelled by four puller-type pod-units all equipped with 5.2 m propellers. Each pod absorbs approximately 27MW power – the forward pods are fixed and the aft pods are azimuthing for ship manoeuvring control. A stern view of the FASTPOD Ropax model is given in Fig. 38.

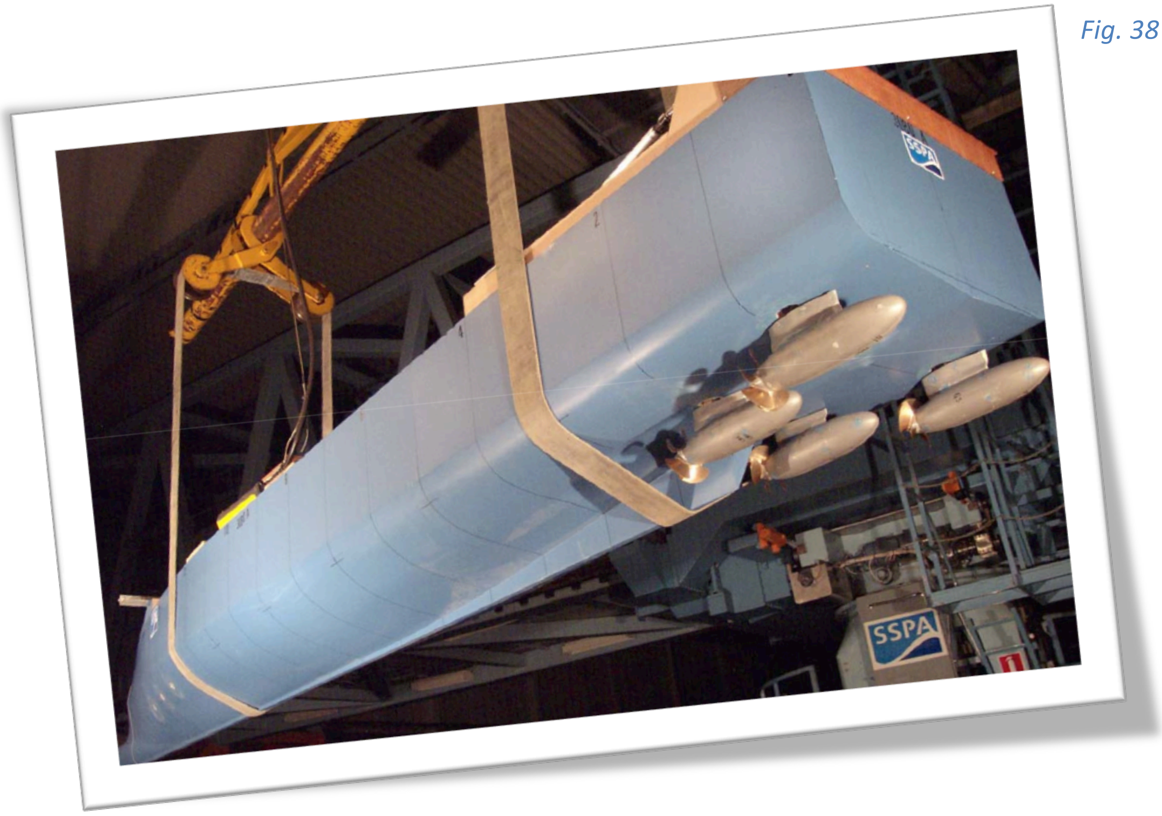


Fig. 38 – FASTPOD Ropax

Free-running model tests were carried out for the FASTPOD Ropax at SSPA in Sweden. The tests were conducted in the facility Maritime Dynamics Laboratory using a 5.7 m model. The four pod propellers were driven mechanically from inside the hull and assume a constant torque model. The thrust and torque is measured on all pods and the slewing stock loads are measured for the port pods only.

The tests considered all the IMO criteria manoeuvres measuring both ship response and induced pod loading. Again, the spike loads associated with dynamic manoeuvring can be observed in the test results as shown in Fig. 42 and Fig. 43. Figure 42 presents the model tests results (in ship scale) for pod side loading when executing a 10/10 zig-zag manoeuvre while Fig. 43 for the case of a 35^{o} applied helm angle. In both figures the appearance of the spike loads is very clear.

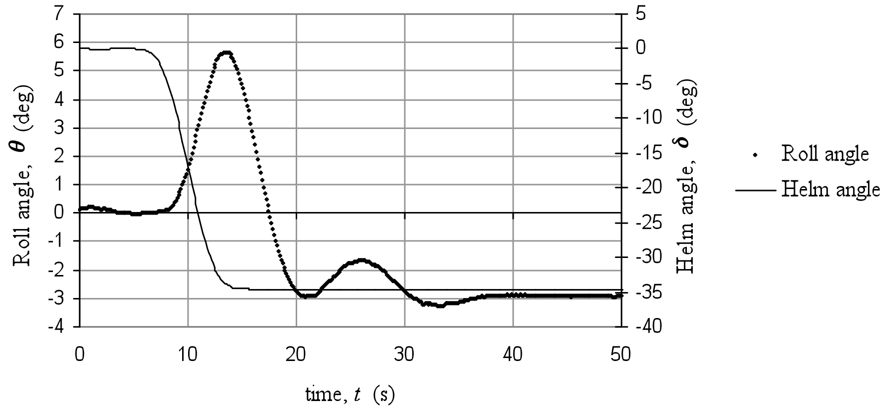


Fig. 39 – FASTPOD Ropax model induced roll in turn

Note how the spike-load causes the ship to first roll in the opposite direction.

One other point worthy of note is the roll behaviour of both ships. While an acceptable list angle was observed in steady turning, a large initial rolling angle was observed at the start of the turning manoeuvre; shown in Fig. 39. This is again most likely related to the spike-loading experienced by the pods during this phase of the manoeuvre. This type of behaviour has significant implications for the safety of pod-driven ships and thus requires further investigation.

6.2 Numerical Simulation of Loads

To investigate the time-dependant dynamic nature of the manoeuvring induced pod-loads, a numerical simulation algorithm was derived. In brief, the main components of the simulation algorithm are herein described.

The ship dynamics are accounted for in the usual manner; using a Taylor series expansion to model the hydrodynamic derivatives. The four-quadrant propeller hydrodynamics are obtained by direct integration of the component blade forces for one full rotation. Similarly, the inclined flow propeller hydrodynamic forces are obtained by direct integration of the component blade forces but also taking into account of the flow incidence. The unsteady propeller forces are accounted for by inclusion of the added mass effect; the Theodorsen[1942] effects were found to be zero for the total propeller. The pod-body lift and drag characteristics take account of the end-plate effects caused by the nacelle and include a form correction. The effect of propeller-race and downwash on the pod lift and drag are accounted for by correcting for the encountered flow velocity and angle. The pod slewing is induced using a PID controller – account is made for both the stock and shaft inertia. Finally, the solution is obtained numerically using the fourth-order Runge-Kutta method for differential equations.

In other word, the same way as in the last section.

6.2.1 Simulation study

To examine further the manoeuvring induced pod loading, the defined algorithm is used to simulate manoeuvring behaviour for both ships. In both cases the calculations are made in the model scale approximating the relevant pod-inertia terms to correspond with the models characteristics. Also in both cases, the PID coefficients are selected to mimic the model scale rudder response.

The results of the 5/5 zig-zag manoeuvre for the OPTIPOD Ropax are shown in Fig. 40. The simulation results demonstrate symmetry about the central axis; showing spike loads of equivalent magnitude for both port and starboard turns. This symmetry is not observed in the model test. This may be caused by some pod-to-pod interaction, which is not accounted for in the numerical model.

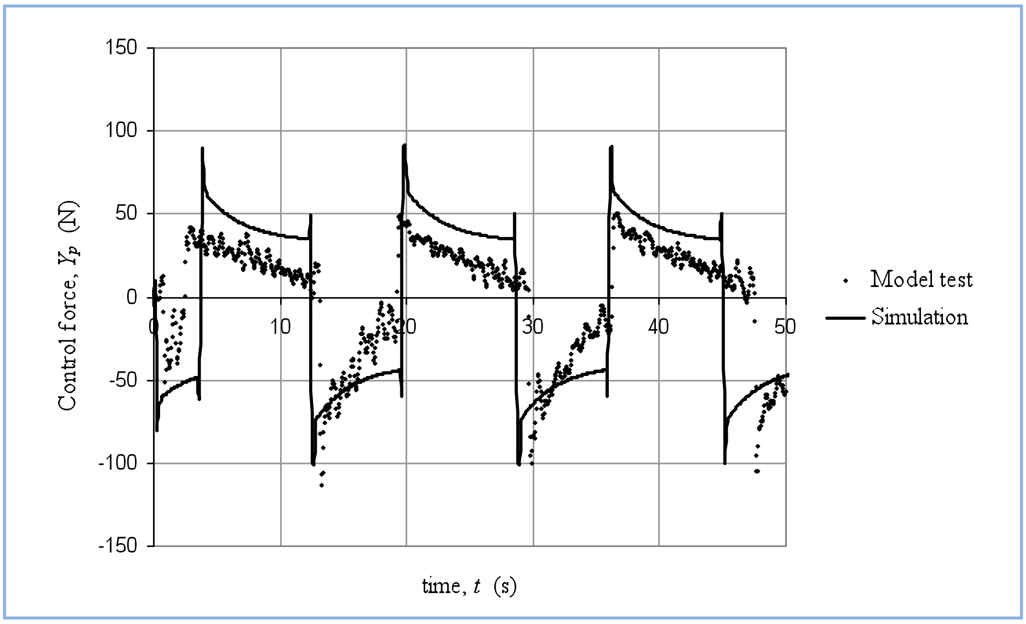


Fig. 40 – OPTIPOD Ropax, measured loads in zig-zag test

The results of the 35 deg turning manoeuvre for the OPTIPOD Ropax are shown in Fig. 41. The simulation results demonstrate some under-estimation for the spiked response. Nevertheless, the nature of the response is modelled very well and the steady state load is predicted accurately.

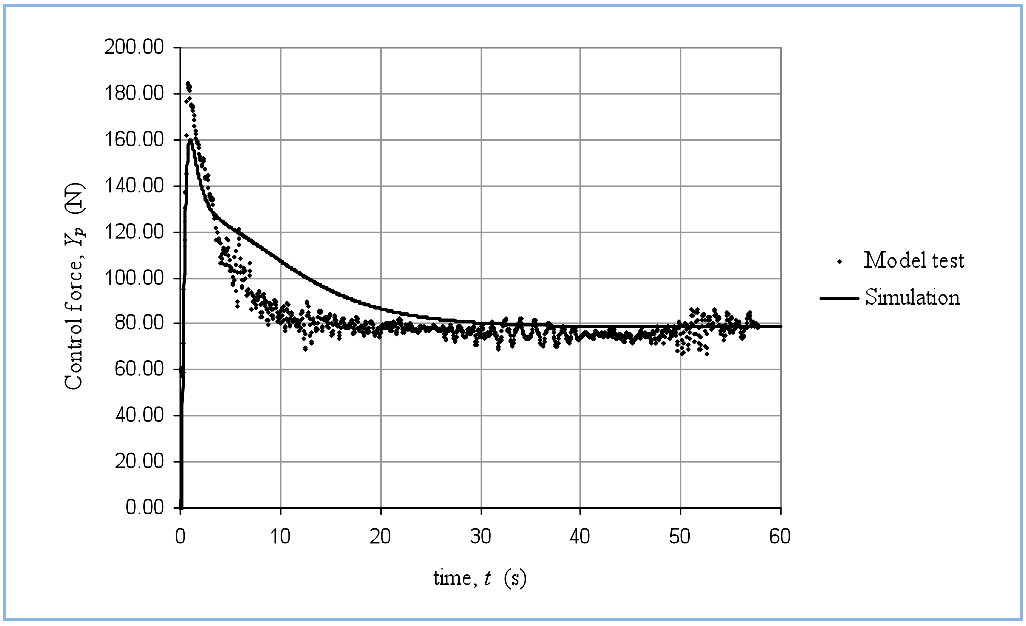


Fig. 41 – OPTIPOD Ropax, measured loads in turning test

The results of the 10/10 zig-zag manoeuvre for the FASTPOD Ropax are given in Fig. 42. The simulated results demonstrate very good agreement with the model test values. Both the magnitude of the spiked response and the steady state load are predicted accurately.

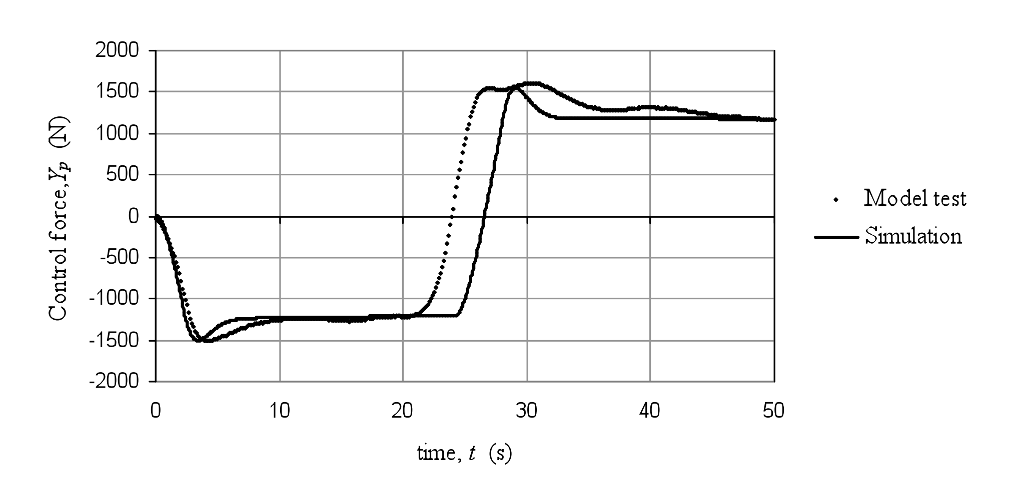


Fig. 42 – FASTPOD Ropax, measured loads in zig-zag test

The results of the 35 deg turning manoeuvre for the FASTPOD Ropax are given in Fig. 43. In this case the spike response and the steady state values are slightly over estimated when compared with the model test results.

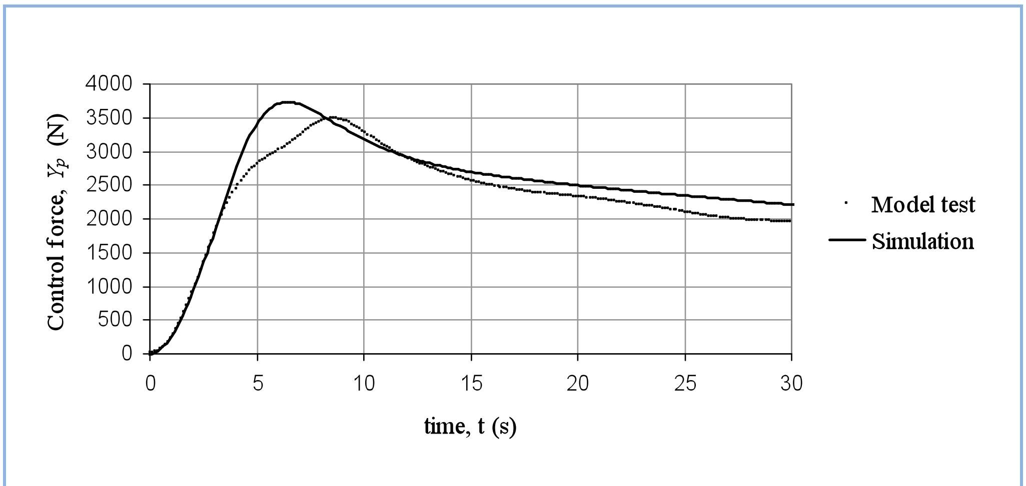


Fig. 43 – FASTPOD Ropax, measured loads in turning test

The simulation algorithm demonstrates that the spike loads are in origin, simply related to the velocity and acceleration characteristics of the system when considered in the time-domain. The results indicated that the simulation algorithm is not sufficient at this stage for the direct estimation of the magnitude of the spike-loads. Regardless, the simulation algorithm clearly demonstrated sensitivity to the chosen parameters and followed the characteristic behaviour of the forces very well. Then, the model can be assumed adequate for the investigation of the relationship between the principal ship and pod characteristics and the magnitude of the spike loads.

6.3 Sensitivity analysis

To investigate the relationship between the input parameters and the spike-loads, a numerical sensitivity analysis was performed. A finite increment between the result R, and its input parameters $\left(\overline{P}_1, \overline{P}_2 \ldots \overline{P}_n\right)$, is used to evaluate the non-dimensional sensitivity θ_i', for the i^{th} parameter $\overline{P}_i$, using a data reduction calculation procedure; given by Eq. 45.

$$\theta_i' = \frac{\overline{P}_i}{R}\left(\frac{\Delta R}{\Delta \overline{P}_i}\right) \qquad \text{Eq. 45}$$

First, Fig. 44 examines the numerical sensitivity of the manoeuvring spike-load for variation in the hull-form characteristics. All ratios and coefficient are varied for a constant total displacement. Also, in each case the relevant parameter is subject to a small increase, thus the sign of the sensitivity shows an increase if positive and decrees if negative.

From the plot it is clear that certain parameters are dominant. First, both the length-draft ratio and the length-beam ratio show a significant decrease in the spike-load. In both cases the length of the ship is increased which is known to increase the course-stability. Second, increasing the block coefficient at the expense of length shows a significant increase in spike-loads. Conversely, this decrease in length is known to reduce the course-stability. In all cases the change in length seems to be the most dominant parameter and in each case the change in course-stability could be assumed significant. In fact, the reduction in course stability will results in an increase in the yaw acceleration for the same manoeuvre. This in turn supports the inference that the spike loads are related to the added mass.

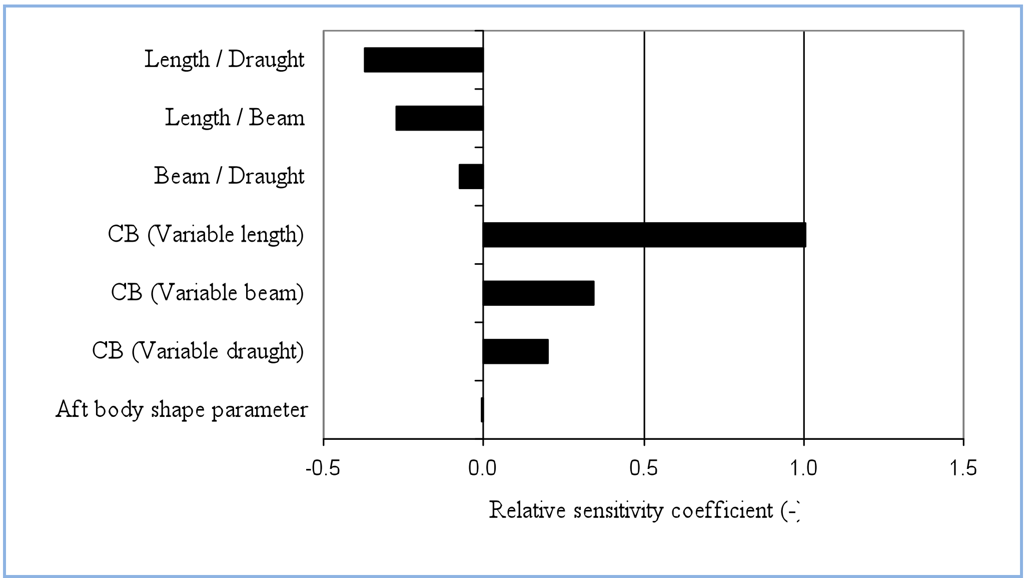


Fig. 44 – Spike load sensitivity to hull-form parameters

Next, Fig. 45 examines the numerical sensitivity of the manoeuvring spike-load for variation in the pod characteristics. Also, in each case the relevant parameter is subject to a small increase, thus the sign of the sensitivity shows an increase in positive and decrease if negative. It should be mentioned that the longitudinal position of the pod is measured negative aft of amidships and increasing the magnitude moves the pod further aft. Clearly, increasing the strut area increases the spike-loading. However, the most significant influence on the spike-load is found to be the longitudinal position of the pod. Again, the acceleration dependence is apparent – moving the pod aft increases the acceleration experienced by the pod due to yawing rotational acceleration.

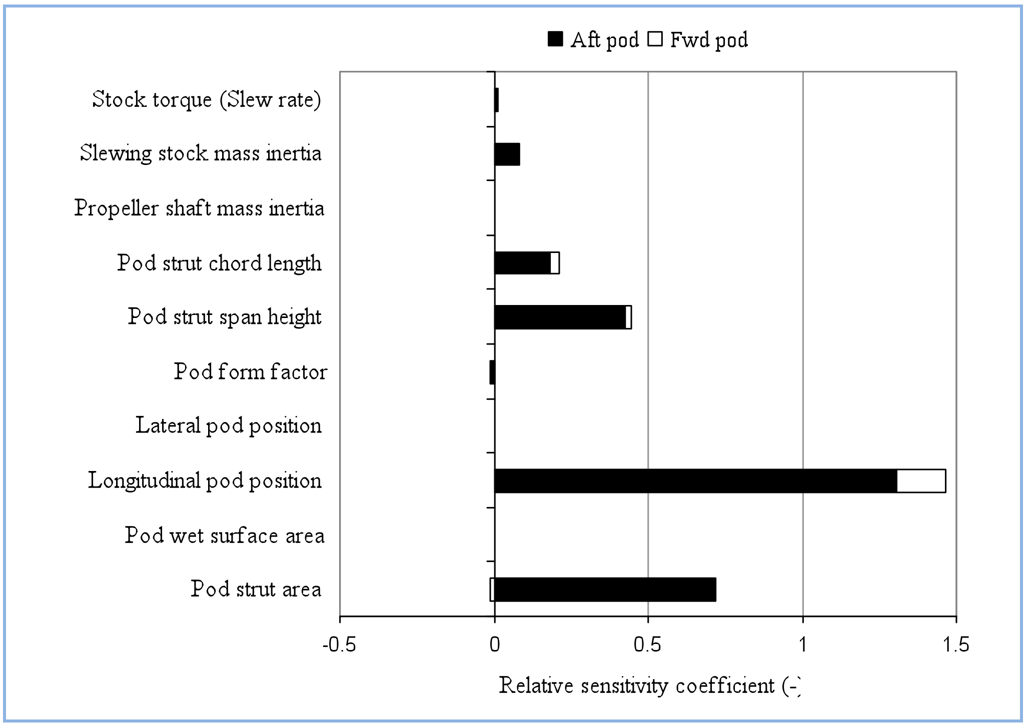


Fig. 45 – Spike load sensitivity to pod parameters

To support the above finding it is also interesting to note the percent increase in load experienced by each ship. The OPTIPOD Ropax has the lowest magnitude of course stability between the two ships and experiences the largest increase in load from the steady state. Generally speaking, pods seem to provide a sufficient control force to steer even the most directionally stable ships. But, hull-forms suited to the application of pods can have poor course stability characteristics – failure to address this at the preliminary design stage can result in a ship that cannot meet the yaw-checking criteria. It is not unreasonable to conclude that the designer of a pod driven ship should attempt to make the hull-form as course stable as possible. After all, it would be very difficult to make a ship too stable for pods but the alternative offers poor directional control, high dynamic spike loads and worrying roll characteristics.

Increase the course-stability and you reduce acceleration dependant loads.

6.4 Gyroscopic precession

Above and beyond the described manoeuvring loads there is another significant force component that is not measured in conventional manoeuvring model tests. The load is generally not measured because although it is induced by horizontal plane motion the reaction is in the vertical plane. In brief, if a mass which is spinning with its rotational axis in the horizontal plane is forced to move on a

Slewing the pod causes an upward force!

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 ship's yawing, and with the motor spinning inside it, will experience a pitching moment. The magnitude of this pitching moment M, is obtained in terms of the motor-shaft-propeller moment of inertia I_{zz}^{pod}, the precession rate Ω, and the shaft rate p; according to Eq. 46.

$$M = I_{zz}^{pod} \Omega p$$ *Eq. 46*

By way of example the precession loading is estimated for the FASTPOD Ropax. The model tests show that the ship is capable of achieving an advance value of about 3.5 ship lengths. Assuming the ship is travelling at 38 knots and experiences a heading change of 90° in 3.5 ship lengths then, the yaw precession rate is approximated. Also, if the pod is slewed in the other direction then the precession components are additive. Taking an approximate value for the system inertia and including the shaft rate, the total precession moment acting about the propeller shaft is in the region of 70 kN.m. As this moment acts about the propeller shaft in the vertical plane it has no impact on manoeuvring response however, the loading has significant implications for both the propeller shaft and thrust bearings and the pod slewing bearings – and will also affect pitch.

6.5 Relative pod loads

To summarise the contributing loads experienced by the pod, the force components are calculated relative to the propeller shaft thrust and torque. Figure 45 gives the relative force components for the FASTPOD Ropax pod; made non-dimensional relative to the propeller thrust. Clearly, the side force induced by the propeller at an angle of incidence to the flow is small in comparison to the thrust. Similarly, the drag of the pod body is also small in comparison to the thrust. However, it is clear that the lift force generated by the pod body is the dominant component; presenting a value nearly three and a half times that of the propeller thrust.

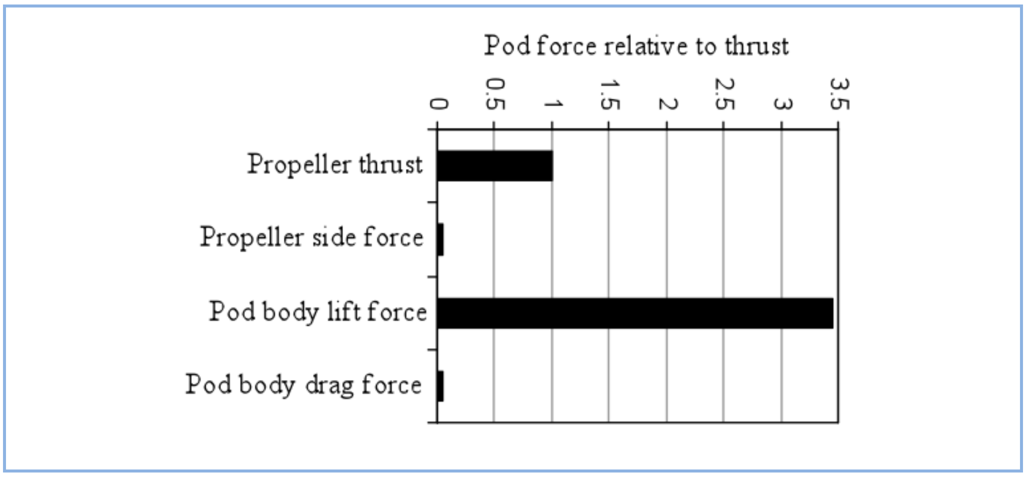


Fig. 46 – Relative pod forces

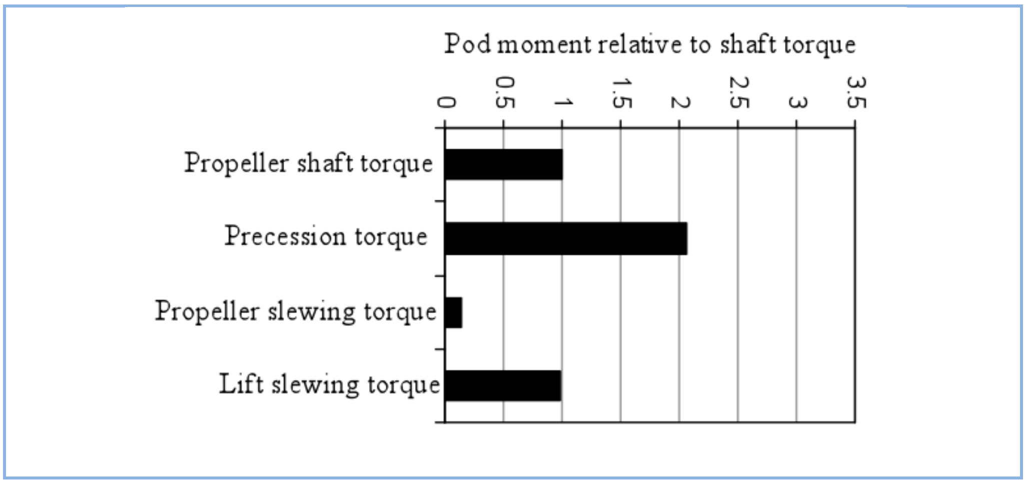
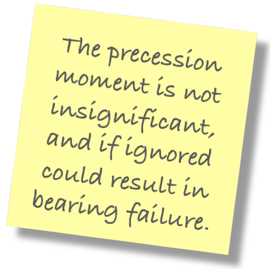


Fig. 47 – Relative pod moments

Next, Fig. 47 gives the relative moment components for the FASTPOD Ropax pod; made non-dimensional relative to the propeller torque. In this case the precession moment is the dominant component; having a value more than twice the propeller torque. The slewing moment induced by the propeller side force can be seen to be small relative to the propeller torque. The slewing torque induced by the pod-body lift force is found to be similar to the propeller torque for this case. However, the slewing torque induced by the pod-body lift is directly dependant on the position of the centre of pressure with respect to the slewing shaft – a small change in this lever can make a large change in the induced moment.



6.6 Discussion on manoeuvring induced loads

The study identifies that pod-drives experience significant spike-loads that are in origin related to dynamic manoeuvring. Though the loads do not impact directly on the manoeuvring response they have significant implications for the structural design and may also impact on the roll stability.

The magnitude of the spike-loads appears to be acceleration dependant and thus sensitive to the dynamic course-stability of the ship. Also, hull-forms suited to the application of pods tend to have poor course-stability. Ensuring that the initial design has positive course-stability may help to reduce the magnitude of spike-loading and induced roll effects. The sensitivity to slew rate is smaller however this is easy to vary and should be kept as low as is practical.

The most significant parameter dictating the control force generated by the pod is the strut; acting as a lifting surface. The second most significant force can be caused by precession loading in the vertical plane – which contributes nothing to the steering control of the ship but will significantly influence the loading on both the shaft and stock bearings.

Reliability Assessment

As part of the reliability analysis, within the FASTPOD project, the manoeuvring reliability of the fast Ropax vessel was examined. Specifically, the safety and risk is investigated in terms of redundancy of manoeuvring components. Remembering that the Ropax has four pods (Pictured in Fig. 38), six failure cases are defined, including thrust failure on each of four pods and slewing failure on each of the two azimuthing pods. The limiting operational criteria are identified and described below. Time-domain numerical manoeuvring simulation is used to examine the response of the ship when operating in various states of redundancy. Finally, the performance of the ship is assed in light of the results and conclusions are drawn.

7 Reliability assessment

The FASTPOD Ropax is principally a roll-on-roll-off cargo and passenger carrying vessel. The ship is designed to operate on Mediterranean Sea routes with a design speed of 38 knots. The ship is propelled by four puller-type pods, the aft two of which are steer-able. Principal dimensions and coefficients are given in Table 4.

Table 4 – FASTPOD Ropax principal dimensions

	Value	Units
Length (wl)	219.64	m
Beam (wl)	29.3	m
Draught (design)	6.5	m
Block Coefficient	0.376	(-)
Aft Shape Parameter	0.070	(-)
LGB (from amidships)	-4.268	m

For the purpose of this analysis it is assumed that there are six specific failure modes. That is, four possible losses of thrust (each of four pods) and two possible losses of steering (the two azimuthing pods). Though it may be possible to have more redundancy in each of these systems, the analysis is performed with only the six described failure modes so as to be compatible with the IMO manoeuvring criteria. Manoeuvring performance failure is assumed to take place when any one or combination thereof of the above described six failure modes prevents the ship form complying with specified criteria. Also, a minimum specified manoeuvring speed must be maintained. In some cases it may still be possible to operate the ship under restricted manoeuvring conditions as described in the HSC [2000], however the normal operation of the ship will not be possible. Then, to clearly define the difference between the normal operation and a 'failure' the interim standards for ship manoeuvring are selected; IMO [1993]. Also, for the purpose of this analysis a minimum speed is assumed to be not less than that corresponding to a Froude Number of 0.1. More specifically the ship shall satisfy the following:

- Advance for an applied 35^o helm angle shall not exceed 4.5 ship lengths;
- Tactical diameter for an applied 35^o helm angle shall not exceed 5 ship lengths;
- Initial turning for an applied 10^o helm angle shall not exceed 2.5 ship lengths;
- Stopping from full ahead shall not exceed 15 ship lengths;
- 10/10 zig-zag manoeuvre overshoot angles shall be within criterion limits;
- 20/20 zig-zag manoeuvre overshoot angles shall be within criterion limits;
- The ship shall be capable of maintaining a speed of not less than 9.2 knots.

7.1 Methodology

For each described failure the ships manoeuvring performance is tested. In the event of failure to comply with the specified criteria, the ship speed is reduced in 10% increments and the tests repeated. If the ship can be manoeuvred within criteria limits at a reduced speed it is considered to PASS. If the ship cannot perform within the criteria limits or not maintain an acceptable manoeuvring speed it is considered a FAIL.

7.1.1 Thrust failure

In each case the available torque is set to zero and the propeller is allowed to turn freely. Then, the simulation is run for sufficient time for the rpm and ship speed to reach a steady state. For the cases where asymmetric failure results in the ship turning, sufficient helm angle is applied to maintain a straight course. The standard manoeuvres are then performed in the normal manner.

7.1.2 Steering failure

In each case the pod is assumed locked in the dead ahead position. The standard manoeuvres are then performed in the normal manner.

7.2 Test Matrix

For the test matrix there are six true/false options resulting in 64 possible combinations; a full test matrix is given in Fig. 48. However, due to lateral symmetry many of these combinations can be ignored. Also, if any one or combination of failures gives a false result then all combinations containing such are assumed false.

The results for the manoeuvring tests for the fully operational case are given in the full report. The results show the ship to meet all IMO criteria and satisfy the design speed of the ship. Next, the results for the case where the thrust on one forward pod is disabled are presented given. Again, the results show the ship to meet all IMO criteria and satisfy acceptable ship speed. Then, the results for the case where the thrust on both forward pod are disabled are given.

And again, the results show the ship to meet all IMO criteria and satisfy acceptable ship speed. Next, the results for the case where the thrust on one aft pod is disabled are given. The results show that the ship fails to meet the Tactical Diameter criteria. Further, it was found that no practical reduction in speed (above the minimum defined limit) would allow the ship to satisfy this criterion. Finally, the results for the case where the slewing on one aft pod is disabled are given. The results show that the ship fails to meet the Advance, the Tactical Diameter and the Initial Turning criteria. Further, it was found that no practical reduction in speed (above the minimum defined limit) would allow the ship to satisfy the criteria.

All further configurations would contain at least one of the last two cases. Thus, all further cases are assumed to fail. The full summary of the results is contained in Fig. 48.

	Fwd Stbd Thrust	Fwd Port Thrust	Aft Stbd Thrust	Aft Port Thrust	Aft Stbd Slewing	Af Port Slewing	Result
1						X	FAIL
2							PASS
3					X	X	FAIL
4					X		FAIL
5				X		X	FAIL
6				X			FAIL
7				X	X	X	FAIL
8				X	X		FAIL
9			X			X	FAIL
10			X				FAIL
11			X		X	X	FAIL
12			X		X		FAIL
13			X	X		X	FAIL
14			X	X			FAIL
15			X	X	X	X	FAIL
16			X	X	X		FAIL
17		X				X	FAIL
18		X					PASS
19		X			X	X	FAIL
20		X			X		FAIL
21		X		X		X	FAIL
22		X		X			FAIL
23		X		X	X	X	FAIL
24		X		X	X		FAIL
25		X	X			X	FAIL
26		X	X				FAIL
27		X	X		X	X	FAIL
28		X	X		X		FAIL
29		X	X	X		X	FAIL
30		X	X	X			FAIL
31		X	X	X	X	X	FAIL
32		X	X	X	X		FAIL

	Fwd Stbd Thrust	Fwd Port Thrust	Aft Stbd Thrust	Aft Port Thrust	Aft Stbd Slewing	Af Port Slewing	Result
33	X					X	FAIL
34	X						PASS
35	X				X	X	FAIL
36	X				X		FAIL
37	X			X		X	FAIL
38	X			X			FAIL
39	X			X	X	X	FAIL
40	X			X	X		FAIL
41	X		X			X	FAIL
42	X		X				FAIL
43	X		X		X	X	FAIL
44	X		X		X		FAIL
45	X		X	X		X	FAIL
46	X		X	X			FAIL
47	X		X	X	X	X	FAIL
48	X		X	X	X		FAIL
49	X	X				X	FAIL
50	X	X					PASS
51	X	X			X	X	FAIL
52	X	X			X		FAIL
53	X	X		X		X	FAIL
54	X	X		X			FAIL
55	X	X		X	X	X	FAIL
56	X	X		X	X		FAIL
57	X	X	X			X	FAIL
58	X	X	X				FAIL
59	X	X	X		X	X	FAIL
60	X	X	X		X		FAIL
61	X	X	X	X		X	FAIL
62	X	X	X	X			FAIL
63	X	X	X	X	X	X	FAIL
64	X	X	X	X	X		FAIL

Fig. 48 – Results of redundancy anaysis

8 Discussion of reliability analysis

The ship can operate at an acceptable speed and will comply with the manoeuvring criteria requirements given in IMO [1993] if, either one or both of the forward fixed pods fail. The ship will fail to comply with the specified criteria if either the thrust or the slewing capability is lost on either of the aft azimuthing pods.

Losing either thrust or steering on a steerable pod is a problem.

Though not specifically examined within the study, the results have significant implications for the more common confederation of two-pod ships. Clearly, the criteria applied herein may be considered harsh for a damage case. Nevertheless, attention should be paid to such redundancy cases when assess the safety and risk of this type of vessel.

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