Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title:

Deliverable 1.6:

Summarise modelling and testing methods capabilities

EXECUTIVE SUMMARY

The analyzed task constitutes the closing part of versatile reviews concerning hydrodynamics of horizontal propulsors. It presents briefly main items of the collected knowledge in respect to such propulsors on basis of predefined needs and expectations . The respective analyzes have shown that under the term “horizontal propulsors” the podded units are meaningfully dominating in analyzed aspects. Despite of it , the gathered knowledge could be gathered in the following groups of reviews which concerns.

- Modeling techniques;
- Testing techniques;
- Validation aspects.

Encapsulation of gathered results was done in the form usable and accessible for project partners. Since results of pod unit investigations were creating the largest and completed data basis, some conclusions and recommendations are based on their testings. This knowledge can be developed relatively easily towards other propulsors investigation techniques taking into account their individual features.

Another essential conclusion concerns the facts that modeling and testing techniques applied for horizontal propulsors are based on the ones which are used now for classical propulsors. From the other side, specificities of novel propulsors are being recognized deeper and deeper.

Having in mind that horizontal propulsors combine in one unit propulsive and steering features, investigations in so called “off design conditions” are strongly recommended in order to recognize their individual features.

The main noticed gaps concern:

- Details of flow details along propulsor body;
- Interactions between propulsor main elements;
- Scale effect in performance predictions;
- Interactions between multiple propulsors.

CONTENTS

1 INTRODUCTION

The present task was elaborated to summarize modelling and testing capabilities. It was assumed to have it based on outcomes of tasks 1.2 through 1.5. Following respective groups of performed works the gathered review results are included in three main themes:

- Findings from modelling reviews;
- Findings from testing reviews;
- Findings from validation reviews.

Moreover, there is included a brief modelling methodology selection table.
A special attention has been paid to novel features of horizontal propulsors and their influences on respective performances. Due to such a presentation any gaps an drawback in analyzed methodologies are getting more visible.

2 FINDINGS FROM MODELLING REVIEWS

2.1 ITTC General Remarks

The International Towing Tank Conference (ITTC) is a voluntary association of worldwide organizations that have responsibility for the prediction of hydrodynamic performance of ships and marine installations based on the results of physical and numerical modelling.

The aim of this task is to review and assess existing modelling and test methods for azimuthing control devices. It was assumed to explore available information concerning presently used representative methods by different research centres and refer them to ITTC recommendations.

As a very new factor in modelling methods are specificities of podded propulsors recognized last years. That is why the most important interactions had to be identified before discussing complete tests methods. However each item could be discussed in scope of available research data. In this aspect an offer of reliable test results is very limited due to costs of investigations and their confidentiality. ITTC procedures and recommendations can be considered on this background as an objective and reliable source of basic data dealt by its versatile committees.

2.2 Steady State Testing Methodologies

2.2.1 Resistance and self propulsion tests:

Main idea of model testing is included in the fact that by doing respective experiments with scale model one is able not only to elaborate predictions for the full scale ships with satisfactory accuracy but compare performances of similar objects as well. In order to carry out, a kind of a global methodology including guidelines for tested samples preparation and results recalculation method is to be determined. It should satisfy the basic physic laws and take into account all interactions identified on real objects. In case of model so called similarity laws should be fulfilled and due formulas should describe basic relationships.

2.2.1.1 Similarity laws:

Similarity laws concern all kind of model tests and they are as follows:

- Geometric similarity: it demands the model form to be identical with the full scale one and the ratios between similar dimensions were the same and equal the scale factor;
- Kinematic similarity: it demands the ratio of full scale times to model scale times is constant amounting the kinematic model scale;
- Dynamic similarity: it demands the ratio between forces acting on the full scale model to the corresponding forces acting on the model is constant, amounting dynamic model scale factor**.**

In case of ship model tests Froude number, describing relationship between inertial and gravitational forces, to be identical for the model and ship. Also Reynolds number, describing relationship between inertial and frictional forces, to be higher than the critical values, individually determined. Equality condition of both Froude’s and Reynolds numbers can not be fulfilled simultaneously at the same model. That is why the Froude number should be precisely modelled during model tests but the Reynolds to be not less than its, individually determined, critical value.

2.2.1.2 Recalculation methods of resistance and self propulsion tests:

- Resistance tests general information**:**

The basic recalculation method of the model resistance values to the full scale was initially elaborated by W. Froude in the second half of the ninetieth century. It divides ship resistance into two components: one dependent on the Reynolds number being recalculated as the flat plate friction force and the second component modelled according to the Newton's law. It makes the total resistance coefficient to be a sum of:

$R_T = R_F + R_R$, and,
$C_T = C_F + C_R$

Where:
R_F - friction resistance of flat plate having the same length as a ship hull;
R_R – residuary resistance – its C_R coefficient is the same for model and full scale ship.

Long lasting practice of this method and growing experience resulted in the further development of this method and components taking into account 3D hull shape, hull roughness and wind exposed areas have been added. It resulted in the concise procedure during ITTC 78. Despite of these changes, the residuary coefficient C_R was further maintained identical for models and full scale ships.

$$C_{TS} = C_R + \frac{S_S + S_{BKS}}{S_S}[C_{FOS}(1+k) + \Delta C_F] + C_{AA} + C_{APS},$$

where:
S – wetted surface of hull or bilge keels;
k - hull form factor;
C_{AA}, C_{APS} - air and appendage resistance coefficients.

- Extrapolation of resistance characteristics of propeller housing:

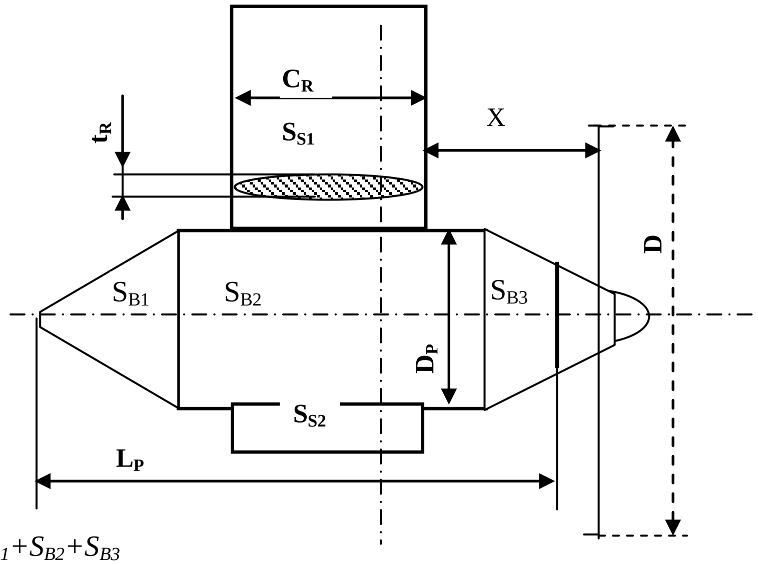


Fig. 2.1

$S_{BODY} = S_{B1}+S_{B2}+S_{B3}$

$S_{STRUT} = S_{S1} + S_{S2}$

$R_{POD} = R_{BODY} + R_{STRUT} + R_{INT} + R_{LIFT}$ - total pod resistance

$R_{BODY} = (1 + k_{BODY})\ R_{f\ BODY}$ - pod body resistance

$R_{STRUT} = (1 + k_{STRUT})\ R_{f\ STRUT}$ - strut resistance

$R_{INT} = \frac{1}{2}\rho V^2 t^2 f\left(\frac{t_{root}}{C_{root}}\right)$ - interaction losses

$$f\left(\frac{t_{root}}{C_{root}}\right) = C_{ROUND}\left(17\left(\frac{t_{root}}{C_{root}}\right)^{2} - 0.05\right)$$ -auxiliary function

$$R_{BODY} = \left(1 + k_{BODY}\right)\left(\frac{1}{2}C_F \rho V^2 S\right)$$ - pod body resistance

$$k_{BODY} = 1.5\left(\frac{D}{L}\right)^{\frac{3}{2}} + 7\left(\frac{D}{L}\right)^{3}$$ -pod body form coeff.

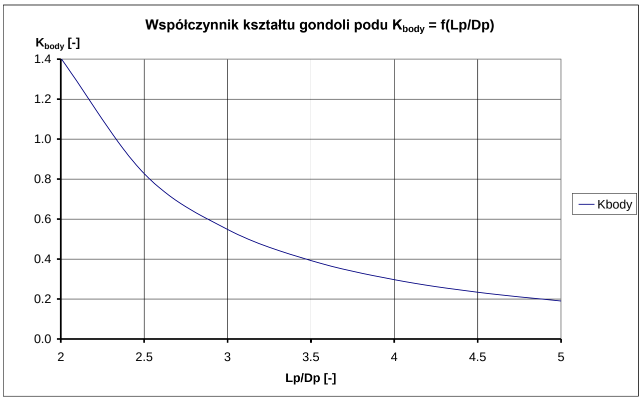


Fig. 2.2 Pod body form coeff. $k_{BODY} = f(L_P/D_P)$

$$R_{STRUT} = (1 + k_{STRUT})\left(\frac{1}{2}C_F \rho V^2 S\right)$$ - strut resistance

$$k_{STRUT} = 2\delta_S + 60\left(\delta_S\right)^4 \qquad \delta_S = t/C$$ - strut form coefficient

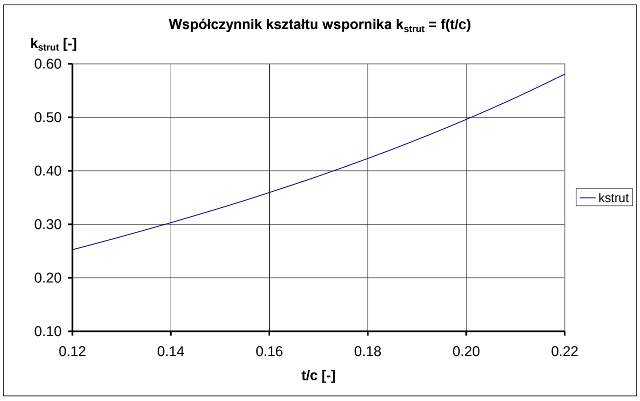


Fig. 2.3 Strut form coefficient $k_{STRUT} = f(t/c)$

- Self propulsion tests general information:

Pod self-propulsion tests are required for predicting the ships calm water performance with the best possible accuracy. Two methods are reported to be now in use.
The first method regards the propeller as the propulsion unit and the pod-housing as an appendage. This method requires a resistance test on a ship model with pod models installed, but without propellers. Then, a propulsion test with the complete pod units is conducted. Also, an open water test on the propeller alone is necessary. The disadvantage of this method is that the strong

interaction between the propeller and pod-housing is not taken into account in the correct way; leading to incorrect propulsive coefficients.
The second method regards the total pod as the propulsion unit. This requires a pod open water test, a resistance test (without the pods) and a propulsion test with the complete pod units. The second method is strongly recommended because it keeps the pod unit with all its internal interactions as one complete unit and this leads to more realistic propulsive coefficients and thus to a better full-scale performance prediction

Since model tests are executed at Reynolds numbers evidently smaller in respect to the full scale ship, the hull model should be towed with use of the friction correction force F_D to model assumed service conditions:

$$F_D = (C_{F0M} - C_{F0S})\, V_A^2\, A_A\, \rho/2$$ - friction correction force

$$P_{DS} = 2\pi \rho_S\, D_S^5\, n_S^3\, K_{QPOS} / \eta_{RP} \cdot 10^{-3}$$ - ship scale delivered power

$$T_{PS} = (\frac{K_{TPS}}{J_{TS}^2})\, J_{TS}^2\, \rho_S\, D_S^4\, n_S^2 \cdot 10^{-3} \quad [kN]$$ - ship thrust force

$$Q_{PS} = \frac{K_{QPOS}}{\eta_{RP}} \rho_S\, D_S^5\, n_S^2 \quad [Nm]$$ - ship shaftline torque

Special attention to be paid at appendages with big wetted surface areas – they demand special treatment due to advanced extrapolation method and a correction coefficient “beta” had to be introduced.
All elements have been included in the ITTC 78 method elaborated during 23 ITTC.

2.2.1.3 *Scale effect in propulsion tests:*

Podded vessel powering predictions are treated in the same way as ships with conventional propellers. Main difference is included only in the definition of propeller efficiency η_o as it is presented in the formulae for propulsive efficiency below:

$$\eta_D = \frac{(1-t)}{(1-w)} \eta_R \eta_0$$

$$\eta_0 = \frac{(J)}{2\pi} \frac{K_{TU}}{K_Q}$$

Pod housing resistance increase due to podded propeller work:

$$\Delta R_{POD} = \Delta R_{BODY} + \Delta R_{STRUT} + \Delta R_{INT} + \Delta R_{LIFT}$$

Scale effect is taken into account by introducing the pod housing drag correction ΔK_{TU} :

$$K_{TU} = (K_{TU})_M + \Delta K_{TP} + \Delta K_{TU}$$

$$K_Q = (K_Q)_M + \Delta K_Q$$

$$\Delta K_{TU} = \frac{\Delta R_{POD}}{\rho n^2 D^4}$$ -

where: ρ - water density
n – propeller revs
D – propeller diameter

$$\Delta R_{BODY} = 0.5\rho S_{BODY} V_{PS}^2 \left(1 + k_{BODY}\right)\left\{C_{FM} - C_{FS}\right\}$$
$$\Delta R_{STRUT} = 0.5\rho S_{STRUT} V_{PS}^2 \left(1 + k_{STRUT}\right)\left\{C_{FM} - C_{FS}\right\}$$

where:

C_{FM} – friction coefficient for pod model acc. to ITTC-57
C_{FS} - friction coefficient for full scale pod acc. to ITTC-57

2.2.2 Manoeuvrability investigations:

2.2.2.1 Model tests:

There are two commonly used model test methods available for predicting the manoeuvring characteristics. One method employs a free running model moving in response to specified control input (helm and propeller); the tests duplicate the full scale trial manoeuvres and so provide direct results for the manoeuvring characteristics. The other method makes use of force measurements on a “captive” model, forced to move in a particular manner with controls fixed; the analysis of the measurements provides the coefficients of a mathematical model, which can be used for the prediction of the ship response to any control input.

- Manoeuvring tests with free running models:

Representative manoeuvres performed with a scale model are the most direct method of predicting the manoeuvring behaviour of a ship. Since, it is recommended to use relatively large models, these ones, being employed for resistance and self propulsion tests, are usually investigated. Large models are necessary to minimize scale effects.

There are limited possibilities to perform standard manoeuvres in typical towing tanks facilities. Alternatively, tests with a free running model can be conducted on a lake. Unfortunately, it demands dedicated test stations and equipment being also dependent on weather conditions.

Apart from giving direct results for due comparisons, certain effort are made now to derive respective coefficients of mathematical models with free running models. The mathematical model is then used for predicting the manoeuvring characteristics of the ship.

- Manoeuvring tests with captive models:

Captive model tests include oblique towing tests in long narrow tanks as well as “circling” tests in rotating arm facilities. Particularly such tests are performed with use of a Planar Motion Mechanism (PMM) which can produce any kind of motion by combining static or oscillatory modes of drift and yaw. The basic principle is to conduct various simpler parts of more complex complete manoeuvres. By analysis of the forces measured on the model the manoeuvring behaviour is broken down into basic elements, the hydrodynamic coefficients. Afterwards, these hydrodynamic coefficients are entered into a computer based mathematical model and results of the standard manoeuvres are predicted by means of this model.

A rotating arm facility consists of a circular basin, spanned by an arm from the centre to the circumference. The model is mounted on this arm and moved in a circle, varying the diameter for each test. The hydrodynamic coefficients related to ship turning as well as to the combination of turning and drift can be determined by this method. Additional tests have to be conducted in a towing tank in order to determine coefficients related to the ship drift. Similarly to tests with use of the PMM, characteristics of the ship can be predicted by means of the respective mathematical model.

Generally, it may be said that captive model tests suffer from scale effects similar to those of free running tests, but due corrections are more easily introduced in the analysis of results.

2.2.3 Modelling of azimuthing control device-to-hull interactions:

2.2.3.1 Flow specificity of pod unit:

In order to analyze interactions between the ship hull and pod unit, it is necessary to know a velocity field around the pod. The typical flow structure along the pod body, in modelled service conditions, can be determined by means of CFD tools, as it is presented below.

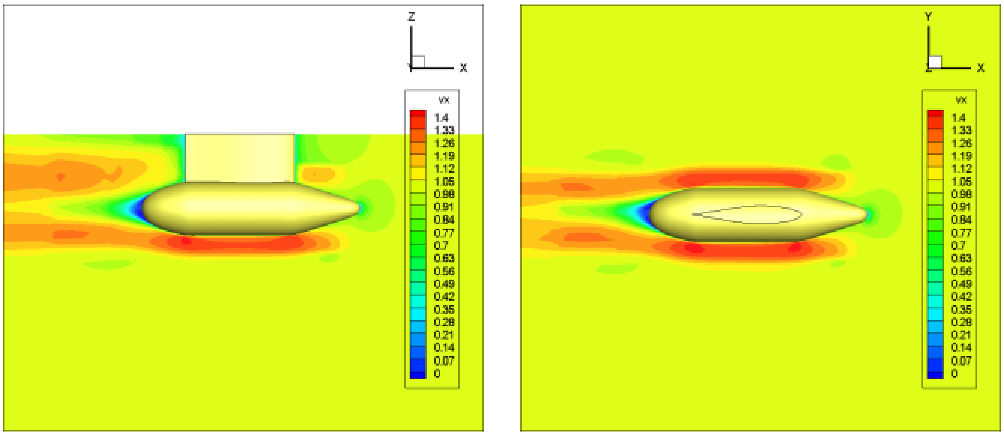


Fig.2.4 Local axial velocities distribution

2.2.3.2 Pod units longitudinal optimum locations on Ropax vessel:

The influence of longitudinal pod locations on resistance performances can be depicted with use of a medium size, fast Ropax vessel as an example.

In two pods or more pods systems, relative big volumes of displacements, on the level of 2x100 cu.m were installed under the afterbody. It influences the specificity of flow along the hull, diminishing or increasing its total resistance. Having in mind these interactions, the hull resistance minimization at the service speed is possible throughout proper locations of units.

The proper bare hull design is necessary to fulfil all requirements put to external pod propulsion. The most important ones are as follows:

- Location within dimensions: L_{OL}, B, T;
- Collision elimination between pods in scope of full angles $0^0 – 360^0$;
- Gap reduction between a pod strut and ship hull in the mentioned angular range,
- Very uniform velocity field in the expected pod installation region, slightly disturbed by pod units presence.

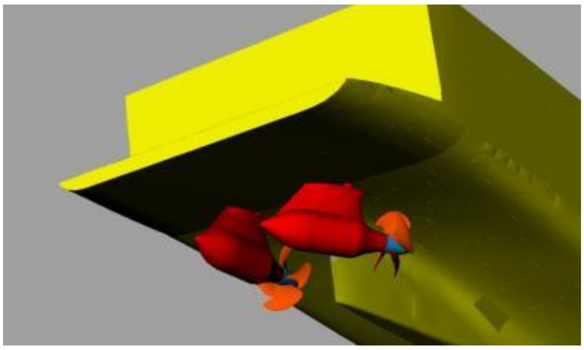


Fig. 2.5 Typical two pods arrangement

The above mentioned requirements can be determined and fulfilled by means of model experiments or by use of CFD tools as well. CFD analyses give worse accuracy but satisfactory results in comparative studies.

1). Analyzed pods longitudinal locations :

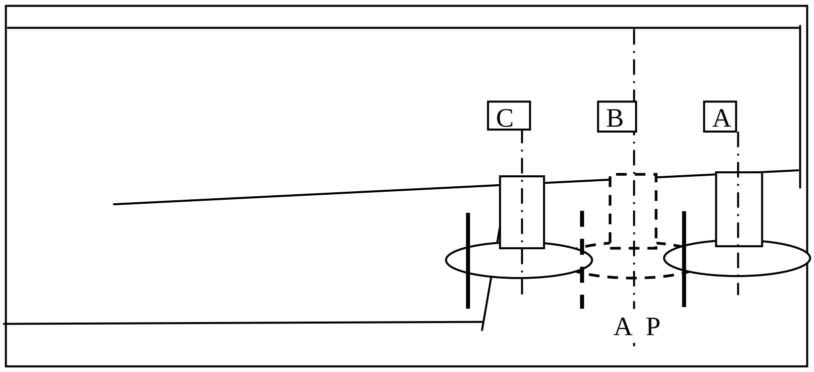


Fig. 2.6 Scheme of pods locations

POD propulsors positions:

- Variant A: x = - 4.5 m; y = ± 7.1 m
- Variant B: x = 0.0 m; y = ± 7.1 m
- Variant C: x = +5.5 m; y = ± 7.1 m

2). Resistance comparison of analyzed variants:

The table below presents the changes of total resistance for each variant and pod unit resistance contributions in the total resistance at Vs=28 knt:

Variants:	Bare hull	Hull + pods
1- bare hull	---------	100.0 %
2 – variant A (x= - 4.5m)	13.0 %	107.3 %
3 – variant B (x= 0.0 m)	10.4 %	104.6 %
4 – variant C (x= +5.5m)	4.1 %	104.5 %

2.2.4 Interactions between multiple azimuthing control devices:

2.2.4.1 General information:

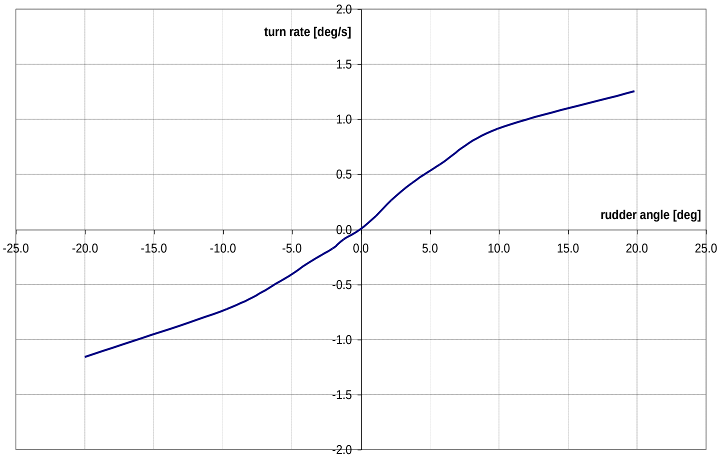
Interactions between multiple pods are known in the very limited range due to big difficulties connected with measurements of such effects. Transitory situations, during manoeuvres executions, are practically not recognized; only selected static situations were studied experimentally or analyzed in numeric ways. Certain interactions can be analysed only by their effects assessing them in respect to basic not disturbed conditions.

There are below given certain manoeuvrability results carried out with use of multiple propulsors which can be compared with respective twin pod results.

2.2.4.2 *Examples of manoeuvrability tests results:*

- ***Four pod units – flapped units as steering devices:***

- **Direct spiral test:**



2.2.4.3 *Comparison of turning tests results for multiple propulsors,V_0 =35 kn:*

Steering devices configuration	Ruddder angle [deg]	Advance X_{90}/L_{PP}		Transfer Y_{90}/L_{PP}	Tactical diameter Y_{180}/L_{PP}	
		True	Criterion.		True	Criterion
Two pods steering + tandem props	+/- 35^0	2.5	4.5	0.8	2.1	5.0
Two pods steering + two pods fixed	+/- 35^0	3.2	4.5	1.1	3.0	5.0
Four pods in CRP mode	+/- 35^0	2.28	4.5	0.9	1.66	5.0

2.2.4.4 Comparison of zig-zag tests results for multiple propulsors, Vo=35 kn:

Steering device configuration	Kind of Zig/zag test	Initial turning ability		1st overshoot angle		2nd overshoot angle	
		True	Crit.	True	Crit.	True	Crit.
Two pods steering + tandem propellers	$10^0/10^0$	1.3	2.5	5.6	12.6	6.6	28.9
	$20^0/20^0$	1.5	-	14.1	25.0	14.1	-
Four pods steering + two pods fixed	$10^0/10^0$	1.7	2.5	4.8	12.6	5.6	28.9
	$20^0/20^0$	1.7	-	13.5	25.0	12.7	-
Four pods in CRP mode	$10^0/10^0$	1.8	2.5	4.6	12.6	6.5	28.9
	$20^0/20^0$	4.2	-	15.4	25.0	17.0	-
Four steering pods	$10^0/10^0$	1.15	2.5	4.0	12.6	6.3	28.9
	$20^0/20^0$	1.2	-	12.0	25.0	11.5	-

2.2.5 Propeller and nacelle interactions including scaling issues and gap-effects:

Particular emphasis was given to the use of different scaling methods of pod-housing-drag and unit-open-water-performance estimations. It was emphasised that, the situation should be even more complex when the differences between model basins and testing methods are considered.
, including:

- propeller gap effect.
- strut gap effect.
- streamlined body effect.

2.2.5.1 Working Point and Off-Design Conditions Concluding Remarks:

The ITTC Committee provide concluding remarks included herein. The Committee concludes that the review demonstrates that the major challenges for pod-drives operation under off-design conditions are associated with finding steady and unsteady loads on the propeller and other components of the pod system in manoeuvring and crash-stop modes.

For the first group of the tasks, it is suggested advisable to apply CFD procedures. Model experiments serve today for pseudo-steady investigations into integral forces (on pod drives in oblique flows). However, latest publications indicate a rapid progress in dynamometers suitable for dynamic testing.

Investigations into the dynamic process of a turning pod drive are rather difficult because one has to simulate not only conventional propeller test parameters like J, but also other aspects like the ratio between the propeller rpm and the pod rate of turn; this has however been shown to be readily achievable and shown to provide good results.

Also, it is important to decide what should be the starting point for force predictions: finding forces on the pod-housing and on the propeller or testing the pod system with the operating propeller. Thus, it appears that future tasks in this field should include:

- Reviewing research and development in procedures for steady and unsteady measurements on various components of pod-drives in steering and manoeuvring modes;

- Reviewing and updating procedures for pod drive cavitation model tests under off-design conditions.

Dedicated simulation studies supported by the limited amount model tests identify that pod-drives experience significant spike-loads in off-design conditions that are in origin related to dynamic manoeuvring and may have significant implications for the structural design as well as impact on the roll stability.

2.2.5.2 Need for dynamic testing methods:

While development is underway, little or nothing exits in the open literature regarding dynamic tests for pod-drives. However, much material in the open literature, and explored above, indicates significant dynamic effects that cannot be accounted for through the normal process of testing; used for more conventional propeller/rudder arrangements. Notwithstanding, valuable insight can and has been obtained through dedicated free-running model testing. Here, a large model equipped with model pods, is operated much like the full-scale ship, in open water, and its performance analysed. When conducting specific manoeuvres, dedicated strain gauges measure forces experience at the pods during such manoeuvres. While indeed providing useful information about both the manoeuvring performance and the experience loads, this method nevertheless has certain limitations. The two main drawbacks being ‘scaling error’ (applicable to all free-running tests) and a ‘precession moment’ (typical to pods).

The first of these, scaling error, is a fundamental restriction caused by the conflicting scaling issues for the ships hull and the propeller. The difference is caused by the different hydrodynamic phenomenon being considered. Specifically, for the ships hull, operating as it does on the interface between two fluids, the free surface proved the dominant effect. For a scale model of the ship to generate the same wave pattern, it is necessary to scale the ship speed in accordance with Froude number. For constant Froude number a smaller model requires a lower ship speed.

In the case of the propeller, the dominant force comes from the viscous nature of the fluid. It is therefore necessary to scale the speed in accordance with Reynolds number rather than Froude number. The unfortunate consequence of this being that the speed must be increased rather than reduced.

The implication for free-running model tests is that for a hull and propeller that have been scaled down by the same ratio, as is necessary, the propeller must operate at the incorrect rpm to drive the hull through the water at the correct speed. More significantly from a manoeuvring point of view is the implication of the propeller wash over the rudder. The force generated by the rudder is strongly dependant on the flow velocity, which in turn is strongly influenced by the propeller rpm. As a consequence of this situation, a free-running model cannot be expected to provide exactly scalable manoeuvring performance results.

It is not hard to see that very similar problems exist with the free-running model tests when investigating pod-driven ships; though the situation is a little more complex. As before, the pod propeller revolutions must be lower than the correct scaled value if we are to achieve the correct ship speed. In this case, not only is the flow over the pod-body incorrect, which acts in some way like a rudder, but the steering thrust is different.

It should be said that, for conventional arrangements, experienced model test centres are capable of judging and compensating for such effects. However, in part due to the lack of full-scale data for validation, it would be a little presumptuous to assume this is the case with pods.

The second problem is the effect of gyroscopic precession. For a real pod-driven ship, the pods have large electric motors inside. These motors can weigh several hundred tonnes and spin at perhaps 100 rpm or more. Weather the ship is yawing in a turn or the pod is being slewed; the effect is the same. That is, the axes of the motor shaftline are moving (sideways) on a curved path in the horizontal plane. Intuitively this would not initially seem to be a problem; the rotation and path of motion being in different planes. However, five minutes playing with a small gyroscope toy will certainly convince you otherwise. The case is that when a spinning mass is travelling sideways on a curved path it experiences a pitching moment about the shaft length. This moment can be large indeed.

When conduction free-running model tests with pods, it is common practice to use a geared drive to turn the propellers. This is necessary to provide sufficient torque within the confines of the scaled pod-housing. In some cases is may be possible to fit a small electric motor inside the pod. However, it is by no means demonstrated, that this can scale correctly the precession moment.

Notwithstanding the above it is by no means insurmountable to provide accurate prediction of the manoeuvring performance of ships, pod-driven or otherwise. The common practice is to perform captive-model tests, performed at the most appropriate scaling function for the hydrodynamic problem in hand (e.g. Froude scaling for the hull and Reynolds scaling for the propeller). The various force coefficient obtained are then combined in a numerical simulation. Once compiled, the simulations model can be validated by comparison with free-running model tests. And once validated, the simulation can be used to predict full-scale manoeuvring behaviour with confidence and free from the previously describe scaling problem.

When trying to apply this methodology for pod-driven ships, the first dilemma is whether to include the pod-body as part of the propeller testing or as a hull-form appendage. Both possibilities have advantages and disadvantages. When testing as a hull appendage, this models well the modifying effect the pod-bodies will have on the shape of the Froude wave and pressure field at the stern. In the same way that a bulbous-bow modifies the pressure at the bow, the pods can modify the flow around the stern of the ship. However, on the real ship the pod-body would operate in the wake of the propellers. This accelerated flow would induce a greater drag on the surface of the body. Alternatively, one can chose to model the pod-body together with the propeller when performing the cavitations tunnel tests; which is the common practice. This accounts well for the viscous components of the flow (describe in much detail in earlier sections of this report). However, this method cannot account well for the steering motion of the pod (slewing) or the turning motion of the ship (yawing). In some cavitation tunnels it is possible to place the pod at an angle-of-attack; giving some understanding of the steady-state steering-forces. However, using conventional equipment, it is not possible to account for dynamic behaviour and the associated forces.

While no such testing is commonly used at present, it is possible here to speculate about what might yield usable results. Firstly, it may be possible to modify the dynamometry of a cavitation tunnel to induce sinusoidal slewing motion. This would in part provide the necessary dynamic force information. While this will not account fully for the dynamic effects of sway and yaw motion, it is quite likely that the dominant forces could be modelled.

In an alternative solution, at twin pod-set can be mounted to a foundation plate and towed down a towing tank. This can be done with both helm-angle and drift-angle; yielding much useful information. This process was performed by CTO within the OPTIPOD project and the results are published widely.

Finally, while no known example of such practice can be offered, one alternative can be suggested. It is feasible to connect a pod-drive, including the propeller (but without the hull), to a towing carriage Planar Motion Mechanism (PMM). In this way, the full range of dynamic effects can be examined. Also, all necessary force coefficients can be obtained and used for simulation. This would of course still neglect the vertical plane moment caused by precession; but as a basic Newtonian problem it can easily be added from first principals.

3. FINDINGS FROM TESTING REVIEWS

3.1 Positive and Negative Effects of Using Azimuthing Control Devices in the At-Sea Condition

As compared with conventional shaft-line propellers, the azimuthing pod propulsion devices are perceived to have the following advantages and disadvantages.

3.1.1 Benefits:

- Better manoeuvrability (even at very low speed), in regard to the turning, initial turning, and yaw-checking abilities;
- Pod equipped with flap and fins bring with additional manoeuvrability ;
- Shorter stopping time and track reach in a crash-stop manoeuvre;
- Lower pressure pulses and noise.

3.1.2 Negative effects:

- Course instability (there has been several reports on course instability of a few podded vessels;
- Large induced roll angle and heel angle in connection with pod-turning manoeuvres;
- Induced side loads in connection with pod-turning manoeuvres;
- Cavitation and vibration at moderate-to-large azimuthing angles;
- Slightly degraded propulsive efficiency.

3.2 Model Testing Methods for Pods in the At-Sea Condition

The same model testing methods as for ships with conventional shaft-line propellers have been used for ships equipped with azimuthing control devices for quite some time now. The manoeuvring performance of podded ships has been assessed with the criteria specified by the International Maritime Organisation (IMO) in a document “Interim standards for ship manoeuvrability, Resolution MSC. 137(76)” .

3.2.1 Model tests on manoeuvrability:

Manoeuvring tests can be executed in two different ways, dependent on the testing purpose, possessed facilities and equipment, as free sailing or captive model tests. Objectives of manoeuvrability test are:

- Verification of manoeuvrability – the fulfilment of IMO criteria;
- Establishment of hydrodynamic coefficients for the manoeuvring equations.

If the purpose is to verify the manoeuvrability of ship in compliance with IMO criteria, then the manoeuvring tests are the self-propelled free sailing type. This type of test is also used to determine the directional stability of ship. The ship model must follow the geometrical similarity as the full-scale ship and the model speed is determined by Froude scaling law. The test speed *V* used in the Standard tests is a speed of at least 90% of the ship’s speed corresponding to 85% of the maximum engine output. The test should be performed in deep, unrestricted and calm water with the ship at full load and even keel conditions. In case the model tests are conducted at a condition different from those specified above, necessary corrections should be made in according with the guidelines in the explanatory notes on the standards for ship manoeuvrability from IMO.

3.2.2 IMO standard manoeuvring tests include the following:

(1) Turning circle test

Turning circle manoeuvre is the manoeuvre to be performed to both starboard and port with 35° rudder angle or the maximum rudder angle permissible at the test speed, following a steady approach with zero yaw rate.

The criteria for *turning ability* are
(a) The advance should not exceed 4.5 ship lengths (L) and
(b) The tactical diameter should not exceed 5 ship lengths in the turning circle manoeuvre.

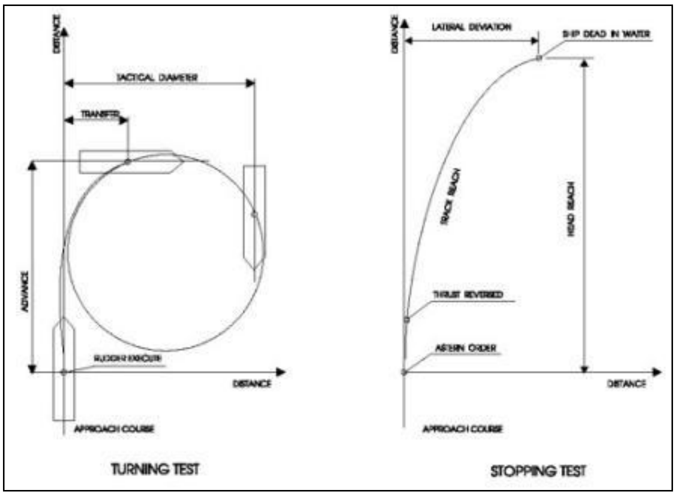


Fig. 3.1 Sketch of turning test and stopping test

(2) Zig-zag tests

Zig-zag test is the manoeuvre where a known amount of helm is applied alternately to either side (port and starboard) when a known heading deviation from the original heading is reached. It includes two tests.

- helm angle 10º/ 10º to both sides
- helm angle 20º/ 20º to both sides

On the base of zig-zag test, initial turning ability, yaw-checking and course-keeping abilities of ship are specified.

The criterion for *initial turning ability* is:
With the application of 10° rudder angle to port/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.

The criteria for *yaw-checking and course-keeping abilities* are:
(A) The value of the first overshoot angle in the 10°/10° zig-zag test should not exceed:
    (a) 10° if L/V is less than 10s;
    (b) 20° if L/V is 30s or more; and
    (c) (5 + 1/2(L/V))° if L/V is 10s or more, but less than 30s,
where L (model-ship length) and V are expressed in m and m/s, respectively.
(B) The value of the second overshoot angle in the 10°/10° zig-zag test should not exceed:
    (a) 25°, if L/V is less than 10s;
    (b) 40°, if L/V is 30s or more; and

(c) (17.5 + 0.75(L/V))°, if L/V is 10s or more, but less than 30s.

(C) The value of the first overshoot angle in the 20°/20° zig-zag test should not exceed 25°.

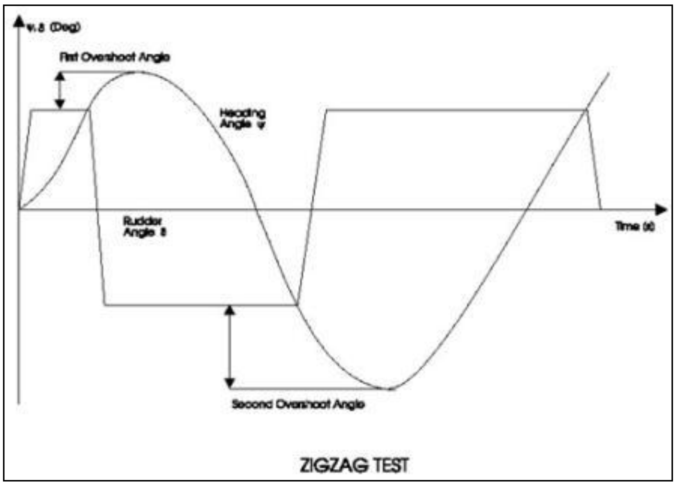


Fig. 3.2 Sketch of zig-zag test

(3) Full astern stopping test

Full astern stopping test determines the track reach of a ship from the time an order for full astern is given until the ship stops in the water.

The criterion for *stopping ability* is:

The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the Administration where ships of large displacement make this criterion impracticable, but should in no case exceed 20 ship lengths.

Typical quantities measured during the standard manoeuvring test are:

- Model speed;
- Propeller rate of revolutions;
- Rudder angle;
- Heading ;
- Position (alternatively 6 DOF position measurement);
- Rate of turn (e.g. by use of gyro).

If test results from the above standard manoeuvres indicate dynamic instability, additional tests may be conducted to define the degree of instability, such as:

(4) Spiral and reverse spiral test

(5) Pull-out manoeuvring test

The second type of manoeuvring tests, captive model test, is carried out with use of Planar Motion Mechanism (PMM) or its equivalents. They constitute a kind of parametric investigation where a model is towed in the tank and parameters describing its movement are changed according to earlier assumed matrix. During tests, model positions, speed and loadings (as explicitly defined forces and moments) are measured. It makes possible to calculate necessary coefficients and derivatives which afterwards are put to the assumed mathematical model. As a result characteristics of any simulated manoeuvre can be acquired.

(6) Drift angle tests (course stability):

In order to get preliminary information of the course stability of the ship transverse forces fore and aft are measured in combination with the self-propulsion tests. The drift angle tests are carried out at the design speed and at a number of drift angles. The propeller rpm is kept constant corresponding to the self-propulsion point at zero drift angle. From the test results the linear stability coefficients Y''uv and N''uv can be determined. The damping coefficients Y''ur and N''ur can be estimated based on statistical data and the dynamic stability lever (Slev) is given by the formula:

Slev = (xg-N''ur)/(1-Y''ur) - N''uv/Y''uv

(7) Different stopping modes

As far as crash stop manoeuvre for pod propulsions is concerned, the braking force can be generated by several modes, as contrary to the conventional propellers where the braking force can only be trigger by reverse rotation of propellers.

There were different numerical studies aiming to compare the response of ship in following stopping modes including:
1). Changing the direction of propeller rotation (reversing the thrust);
2). Turning the pods around;
3). Turning the pods around while reducing the thrust;
4). Turning the pods to 60° in opposite directions while reversing the thrust called “Indirect Manoeuvre”.

The results of the analysis demonstrate that reversing the thrust by mode 1 provides a low, continuous load on the pod, resulting in the longest stopping time and distance. The analysis does not however consider the poorly distributed and unsteady forces experienced by the propeller. Comparison of stopping by turning the pods by mode 2 demonstrates that far greater forces can be generated by the pod system than can be generated by the propeller alone. The results show that a reduction in MCR, while extending the stopping distance, does not significantly reduce the peak forces on the pod. This is considered to be due to the propeller/shaft/motor mass inertia, initially sustaining an rpm value not possible with the motor torque alone. Clearly, it is possible that this inertia-sustained rpm could induce high propeller stresses. The indirect manoeuvre mode 4 demonstrates the shortest stopping time and distance. The results show a more sustained braking force but with significantly lower peak loads than when turning the pods around. A further advantage of the indirect manoeuvre is quoted to be that induced asymmetry between pod helm angles can provide large steering forces; resulting in a safer, faster and far more controlled stopping operation. The proposed model does not take into account the effect of interaction between pods nor cavitation which can be apparent, particularly at increasing helm angles.
It is therefore important to clarify in the report which stopping mode is applied in the standard full astern stopping test. It is also recommended to investigate response to other alternative stopping modes whenever applicable.

3.2.3 Response under extreme steering:

By *extreme steering* it is meant that the podded propeller is slewed through angles exceeding 7~10°, which in practical terms means a range of 15~30° (ITTC, 2005a). Under such extreme steering of pod units, it has been observed in experiments and also in mathematical simulations that the podded ships exhibit several unique responses.

3.2.3.1 Large induced side loads:

Turning the pod in the extreme mode will exert large manoeuvring-induced side loads on the entire pod unit due to their high acceleration dependency. There are presented in the thematic literature model test results showing spike-like loads experienced on the pods of two different ships. The magnitude of the shown spike loads is to be acceleration dependent and most sensitive to the dynamic course stability of the ship. Though these loads do not impact directly on the manoeuvring response they have significant implications for the structural design of the pod and its seating at the aft end of the vessel.

3.2.3.2 Induced roll motion:

During a steady turning of the pods, a large induced initial roll angle (motion) and a subsequent moderate heel angle was noted by Woodward et al. (2005b) in the same time when the large induced side load was observed, implying a close connection between these two responses under the turning manoeuvre.
Within the same context the merits and drawbacks of the manoeuvring characteristics related to the application of podded propellers were investigated. They drew attention to the heel/roll behaviour while manoeuvring with the pod-driven ship; although the turning ability itself was not a problem when judging the applicability of podded propellers. These behaviours are attributed to high turning rates which induce large gyration forces and thus large roll motions. The resulting roll angles in turn can affect the turning rate and the course stability. Based upon their database they demonstrated 28° maximum roll and 17° constant heel at high speed and large steering angles. They claim that maximum roll angle greater than 13° and constant heel angle larger than 8° are cause for concern and these are not covered by the current IMO criteria. The steering related heel/roll behaviour has also been the subject of investigation by other institutions. It is advisable to measure the side force and heel/roll angle variations in a large turning manoeuvre.

3.2.3.3 Cavitation at off-design azimuthing:

There is a high probability of cavitation when the podded propulsor is rotated by large azimuth angles due to the reduction in the advance ratio and the increase in the incidence angle. Cavitation test at large off-design azimuthing angles appears to be necessary for pod-driven vessels. The test procedure for cavitation observation on podded propeller is described in detail in the ITTC’s recommended procedure 7.5-02-03-03.6.

3.2.4 Model tests on seakeeping:

Seakeeping deals with the dynamic motion of ship in a seaway. The complex dynamic motion is a mixture of surge, heave, sway, rolling, pitching and yawing in response to the action of the ocean waves, superimposed onto the ship’s ahead motion and any sideways drift it may take due to the wind and/or current. The common understanding of seakeeping capabilities is that the main dimensions of ship and hull type are essential parameters. The shapes of the fore and aft body of hull are also of some importance. The choice of pod propulsion for a vessel and the associated stern shape could consequently have some influence on the seakeeping properties.

3.2.4.1 Objectives of seakeeping tests are to:

- Determine operational limits;
- Measure design loads;
- Optimize design with respect to seakeeping performance;
- Capsize and safety studies;
- Development and testing of motion damping systems;
- Investigate added resistance and speed loss due to waves.

The 23rd and 24th ITTC Seakeeping Committee (ITTC, 2005b) have established procedures recommended for performing seakeeping model tests of ships equipped with conventional shaft-line propellers, including:

(1) Procedure 7.5-02-07-02.1 for model tests on linear and weakly non-linear seakeeping phenomena.
(2) Procedure 7.5-02-07-02.2 for added resistance and power increase in irregular waves.
(3) Procedure 7.5-02-07-02.3 for experiments on rarely occurring events.

These tests are directly applied for seakeeping study of podded vessels today. Analogous to manoeuvring tests, seakeeping model tests can be executed in two different ways, as free sailing (free-running) test or captive test.

The free sailing tests, the most common type of tests, are performed to measure various response of ships (motions and accelerations), as well as the internal global or local (slamming) forces. The captive tests are performed primarily to verify and validate numerical methods or mathematical models. In a captive test for seakeeping study, the total forces on the model are measured. The model may be given forced motions or being fixed in arriving waves.

Typical quantities measured during a free sailing seakeeping test for podded ships are:

- wave height;
- ship speed;
- rate of propeller revolutions;
- POD x-force, (ship's co-ordinate system);
- POD y-force, (ship's co-ordinate system);
- POD angle;
- steering flap angle, if any;
- surge, sway, heave;
- roll, pitch, yaw;
- wave heading;
- longitudinal acceleration aft, x;
- lateral acceleration fore, y1;
- lateral acceleration aft, y2;
- vertical acceleration aft PS, z1;
- vertical acceleration fore, z2;
- vertical acceleration aft SB, z3.

3.2.4.2 Special consideration of seakeeping tests for pod-driven ships:

- **Slamming**

The flat bottom of the aft-body of a podded ship is likely an area subject to slamming due to the special design of the stern to accommodate the pod unit. Slamming loads are often characterised by high peak pressure values in short duration. The noise and vibration problem due to slamming may cause an issue of onboard comfort for cruise liners. Therefore a test of importance for pod-driven ships is to measure the slamming force in a free sailing test conducted in selected irregular waves. By placing the proper transducers in the risk area, the local slamming force acting on the model can be measured.

- **Course keeping in waves**

It is of added value to examine the course keeping ability under environmental waves for podded ships, especially when they have revealed poor course stability during manoeuvring tests in calm water.

- **Dynamic stability in waves** (rarely occurring event)

Dynamic stability in waves is related to the property of motions under broaching, bow dive and coupled pitch-roll-yaw motions caused by groups of large regular waves. Dynamic stability and capsize are often tested in large regular waves.

- **Parametric roll**

A very important operability aspect for cargo ships is the risk and extent of parametric roll in head sea and following sea conditions, because excessive roll can result in significant loss of gods from the deck .

4. FINDINGS FROM VALIDATION REVIEWS

4.1 Introduction:

The aim of this task is to review the compliance to existing modelling validation methods for harbour and at-sea condition for ships equipped with azimuthing control devices. The objective is to establish the extent to which existing methods are validated for simulation purposes and to identify appropriate sources of validation data. The main area of focus will include:

- Survey of ITTC and other scaling procedures and recommendations; specific to manoeuvring related issues;
- Survey of extent of validated models from full-scale data;
- Explore possibility to validate modelling and simulation methods by comparison with manned-model output data;
- Discuss and indicate together with specialists in marine simulations and marine training what capabilities are validated and what capabilities are difficult or impossible to validate.

4.2 Scaling Procedures and Recommendations

4.2.1 General:

In manoeuvring tests with free running models, the propulsors are used to give the model the desired speed i. e. to produce the thrust to keep the desired speed and also to produce a propeller induced flow over the rudders.

Froude scaling of speeds is generally applied and turbulizers (wire, sand strips or studs) should be added, as it probably will give a more realistic boundary layer development and pressure distribution along the hull.
Scale effect may be generally neglected, at least for conventional merchant (displacement type) vessels with propellers working in the wake of the hull and the rudder is situated in the propeller slipstream.
Fortunately two phenomena- the larger model wake fraction and the larger model resistance- tend to even out in the rudder force.
As a result of these scale effects, rudder effectiveness of a model may generally be overestimated compared with that of a real ship.
Accordingly, free models tend to be more stable (or less unstable) with respect to course keeping stability. This effect is typically less significant for fine ships because of their inherent stable course keeping ability.

4.2.2 Free running model tests:

In order to minimize the scale events during free running manoeuvrability tests, it is recommended to use as long model as it possible, about 6 meters long. Such tests can be carried out in either model or ship load conditions. The model load conditions correspond with the increased load of the propulsive system of a tested model.
Sometimes, especially for high-speed ships with low wake fractions, it might be necessary to compensate the larger friction resistance of the model with an additional propulsion device, e.g. a wind fan or air jet device.
Since, rudders are normally positioned in the wake field behind the ship and in the propeller race, i.e. in the very disturbed and turbulent flow, the Reynolds number effect for the rudder force may be neglected. Nevertheless sand strips or studs are sometimes applied to the rudder.
In case of twin propulsors systems, it is recommended to use individual electric motors cooperating with steering computers, instead of complex gears. Such a solution can do the work of the inner propeller more realistic during modelling the turning manoeuvres.

4.2.3 Captive model tests:

Captive manoeuvrability model tests are expected to deliver versatile coefficients for respective mathematical models. In such investigations forecasting accuracy essentially depends on quality of the mathematical model which should include elements of the scale effect.
It results in the fact that shorter hull model, about 3 meter long, can be satisfactorily used for captive model tests. Shorter models can seriously reduce excessive loads of PMM mechanisms bearing systems while models are towed with the biggest drift angles.

4.3 Extent of Current Validation

The following text is extracted directly from the ITTC report and reviews information in the open literature related to the application of the IMO manoeuvre criteria to pod-driven ships.
There reports on results of the sea trials for a Fantasy Class cruise vessel Elation; driven by twin puller-type pods. Comparisons of the achieved turning circle parameters are made with a conventionally propelled sister ship; demonstrating a 38% improvement in Tactical Diameter in favour of the pod-driven version. However, speed losses while

turning the pod-driven version were noted as significant. Also, good yaw-checking is observed that comfortably meets the criteria. Conventional emergency stopping tests were performed by reversing the shaft rotation and achieving a head-reach of 2.78 ship-lengths. Also, an unconventional stopping test is examined where the pods are slewed through 35° while simultaneously reversing the thrust. In this case the paper proposes replacing the traditional parameters by a Sweep-reach and Lateral-sweep; achieving 2.4 and 2.2 ship-lengths respectively.

Another author discussed the hydrodynamics trends in the hull-lines of pod-driven large cruise vessels. In this study he emphasised the problem-free manoeuvring characteristics of large L/B ratio vessels, particularly those of Panamax size. He claims that these vessels met the IMO criteria by a better margin than conventional types; giving an example of the smaller turning diameters of the Festival and Radisson series for the same helm angles.

There were also met reports on the development work with the world’s largest ever cruise ship (Voyager of the Seas) driven by two steerable puller-type and one central pusher-type fixed pod. Their report focused on the selection of the best aft-end and propulsion system combinations with respect to the powering, seakeeping and manoeuvring characteristics of this vessel including model- and full-scale measurements. Although no specific reference has been made to the IMO standards, excellent manoeuvring capability was reported including the model and full-scale results of the turning circle and zig-zag manoeuvres. However, specific emphasis has been placed on the necessity for small heel angles during manoeuvres; a 4° of maximum heel angle restriction was enforced for safety reasons.

Some investigations were directed to the manoeuvring performance of pod-driven ships and make comparison with a database of results for conventionally propelled vessels. The turning circle performance of pod-driven ships is examined and found to be superior when compared to a database giving results for conventionally propelled vessels. The paper finds that, for the pod-driven ships examined, the yaw-checking criterion is satisfied however comparison with similar conventionally propelled vessels presented some minor improvement in favour of the latter. The paper notes that, the classification society and SOLAS requirements treat the pod as azimuthing thrusters and hence apply 9°/s slewing rate; compared to a value of 2.32°/s for the rudder. The authors also make note of large induced roll angles observed when manoeuvring the pod-driven ships. They recommend that the IMO should provide criteria regarding acceptable heel angles during manoeuvring and should require model tests and/or trials to demonstrate compliance with the criteria.

The EU sponsored project OPTIPOD investigated all aspects of pod-driven ships. One of the project work packages was dedicated to the analysis of the Safety and Risk issues related to manoeuvring. Four ship types were used as case studies including: a Ropax; a Cargo ship; a Cruise ship; a Supply ship. The work included the development of manoeuvring performance preliminary design tools, captive model testing, free-running model testing, full-scale sea-trials, a manoeuvring performance simulation study and a final report assessing compliance with the IMO manoeuvring criteria. The results of the free-running tests and sea-trials demonstrate that three of the ships satisfy all of the criteria while one ship cannot meet the yaw-checking criteria. A review of the manoeuvring performance demonstrates, using a frequency based analysis, that two of the ship are course stable and two are not. The two stable designs are shown to satisfy the initial turning criteria by a good margin. Of the two unstable designs, one is shown to have sufficient closed-loop stability and one does not.

There is also presented a comparative study of the manoeuvring performance when using both conventional propulsion and pod drives on a Ropax. The conventional arrangement has twin shafts and rudders and the pod-driven version has twin puller-type pods; the hull-form is the same for both. The paper argues that, for a conventional arrangement, it is difficult to increase the control force without also increasing the stabilising effect of the rudder however, with careful design this problem can be addressed using pods. The paper presents results showing a global improvement in favour of the pod-driven version. The pod version gives some 12% reduction in Advance, 19% reduction in Tactical Diameter and more than 23% reduction in the $10^o/10^o$ zig-zag overshoot angles.

There wre performed model tests and full-scale trials with a Panamax size cruise vessel; driven by twin puller-type pods. The turning circle tests were conducted in model- and full-scale and compared. Some overestimation of turning parameters is observed for the model-scale predictions however both results meet the criteria values with a substantial margin. Similarly, the yaw-checking tests were conducted in model- and full-scale and compared. Good comparison is observed between the model- and full-scale overshoot angles and again the criteria are met with a substantial margin. Based upon an analysis of different turning tests, a large difference in the effective attack angle from the inner and the outer pods is observed. It is argued that, possible scale effects in the local flow direction may explain some part of the difference observed between model and full scale.

Some authors draw attention to the effect of cavitation during manoeuvring based upon their observations during full-scale trials with puller-type pods. They recommended no more than $5\sim7^o$ helm angle for course keeping. They also observed that the risk of cavitation during steady turn was far higher than the effect of ($10^o\sim15^o$) oblique inflow angles. This was associated with high speed losses and hence overloading of the propeller due to greater drift angle and yaw rates created by the large steering forces. They recommended some rationalistic automatic control for propeller speed during control at least under non-emergency conditions.

There was investigated the crash stop behaviour of a twin pod vessel using an alternative manoeuvre which is executed by simultaneously turning the pods through 180^o without reversing the propeller. They demonstrated that this provides significant reduction in the stopping distance and time compared to the traditional crash stop. However, the propeller blades, particularly at the root regions, will experience unacceptable stresses when helm angles are at 76^o (turning outwards). They also demonstrated that this dangerous mode can be reduced by performing the manoeuvre with reduced power which still results in an effective crash stop manoeuvre compared to the traditional methods. While the full-scale manoeuvres with the proposed methods presented 27% shorter stopping distance and 26% shorter stopping time, the authors recommend further investigations to generalise the method for different speed, size of ships and different pod drives.

Finally, there were examined four different manoeuvring modes to crash stop a pod-driven ship using a time-domain simulation. Amongst the four modes, turning the pods to opposing angles and reversing thrust (i.e. crash stop by indirect manoeuvre) was shown to provide minimised loads while at the same time maintaining a more controlled manoeuvre.

The Committee identifies that pod-driven ships may or may not satisfy the manoeuvring criteria. No examples were found where pod-driven ships have failed to meet the turning circle and initial turning criterion. In general, the turning performance of pod-driven ships appears to be superior when compared to equivalent conventional arrangements. However, some pod-driven ships are identified that fail to meet the yaw-checking criterion. In fact, the change in hull-form necessary for the introduction of pods is identified as having a tendency for less course-stability.

4.4 Extent of Validated Models from Full- and Model-Scale Data

Two types of data can be used for validation of mathematical simulation models. The first is the full scale measurement data (e.g. in sea trials or specially-targeted full scale measurements). The second and the main source is the experiment data obtained in various model tests.

4.4.1 Source of full-scale data

In many of the larger ACD research project full-scale measurements have been conducted. The major part of these measurements is not reported by public reports. In the following sub-sections some sources of full-scale data are reviewed.

- **Pods-in-service**

Pods-In-Service is probably the most extensive project of full-scale measurement of ship with azimuthing pods. The project included full-scale measurement on four ships. Two cruise ships (GTS Summit and Radiance of the Seas), one RoPax (Nils Holgersson) and one ice breaker (Botnica). Pod- and hull forces were measured. Also pressure pulses and cavitation was measured. Measurement was carried out during see trial and on long term basis during normal operations.

- **Tempera and Mastera - DAT-tanker**

These are so called DAT tanker (Double acting tanker) equipped with one pod unit of 15 MW. The ships were built by Sumitomo Heavy Industries. The first vessel, Tepera, was delivered in 2002. Result from sea trials are reported and compare with model scale tests. These tests include speed-power measurement and manoeuvring test. There are discussed in detail the different methods of prediction from model-scale to full-scale and project it on the sea trials carried out. The paper reports also performance test in ice. Another paper describes the development work and model tests and compare it with full-scale test. The manoeuvring model tests were carried out for pod with and without a fin below the pod house. The tests also show performance when going astern.

- **Elation**

This is one of the first cruise ships built with pod propulsion. She was taken into service 1998. The thematic reports present widely the sea trials and the model tests and hydrodynamic development of this vessel.

4.4.2 Source of model test data:

The extensive experimental data useful for validation are produced in OPTIPOD project technical reports and subsequent publications like papers presented during T-POD 2004 and T-POD 2006 confrences..

4.5 Modelling and Simulation Methods by Comparison with Manned-Model Data

The modelling of the performance of a conventional (rudder and propeller) propulsion and control system or an ASD (azimuthing control device) is different from the simula-

tion technique. Both can be validated separately (e.g. measurement and calculation of forces), but if test results of manoeuvres with models are used for validation purposes, both modelling and simulation are always used in combination and cannot be judged separately.
In comparison with free running model tests the measurements of ship manoeuvres using manned models always contain the human element which influences the results. A comparison of the differences between the two types of model tests illustrates this.

4.5.1 Free running model tests

In free running model tests the model is controlled by a processor which gives the orders to the actuators to perform a special manoeuvre. Dependant on the type of manoeuvre to be carried out a special analysis of available inputs is performed to control the e.g. rudder. Dependant on the type of test this program is more or less complicated but still simple enough to describe the manoeuvre in an unambiguous way.

Turning circle:

Starting with a straight run with constant speed the rudder is deflected to a predefined angle. The manoeuvre is carried out until a certain course deviation e.g. 360°) is reached.

Zig-zag-test:

Starting with a straight run with constant speed the rudder is deflected to a predefined angle δ. When the course deviation has reached a certain value ψ the rudder is changed to the opposite angle $-\delta$. When the course deviation $-\psi$ to the other side is reached, the rudder angle is changed again to δ. The ending criterion is fulfilled, when the course deviation reaches the value of ψ for a second time.

Evasion test:

This manoeuvre is carried out on inland waterways, because it gives an indication of the turning ability without using much space to the sides. It is identical to the zig-zag-test with the difference, that instead of the course ψ the yaw rate r is used.

All these manoeuvres can be carried out very precisely and they can be repeated many times with always nearly identical results. Differences in the results are normally due to slightly different starting or environmental conditions like wind. This fact of the repeatability is of major importance to validate simulations because a simulator is able to carry out exact manoeuvres. In comparison to model tests a simulator is completely independent if the starting and environmental conditions because these can exactly be predefined.

4.5.2 Tests with manned models:

The standard manoeuvres carried out with free running processor controlled models can also be carried out with manned models. The main difference is that the manned model is controlled by human beings, normally a captain and a helmsman.

The procedures to be followed for a standard manoeuvre can also be carried out by the way of watching sensors, giving commands and executing them manually, but this incorporates a lot of errors due to the human influence.

Observation and command:

A sensor like the compass is observed by eyes and the values are read with a limited accuracy. The moment, when the operation of an actuator has to be performed is announced by an oral command including delays to reaction times.

Execution:

The helmsman operates the actuator e.g. the rudder. He as human being also has his delays due to reaction times. The result of the execution is a certain value of the actuator which in the rarest case is exactly that what was ordered by the captain. If for example a rudder angle of port 20 is ordered the result will be something between 19 and 21 degrees, which is sufficient for a real time situation where a manned model is used for training purposes of captain and helmsman.

Recorded motion parameters of a standard manoeuvre carried out with manned models are not sufficient for a manoeuvre used for validation purposes.

In spite of the problems with the human influence there is a possibility to use the results of manned model test. Assuming that not only the motion parameters like course, heading, position and speed are recorded but also the rudder angle and the settings of the engine are stored as a time history with sufficient precision a really full set of data is at disposal for validation purposes.

Normally a simulator only has the possibility to execute programmed standard manoeuvres but it is theoretically and practically possible to use the time history of the actuator activities of a manned model test as input stream for a simulator. In that way the problem with the human influence is overcome because the simulator exactly does, what the helmsman did during the execution of the manoeuvre. Now the recorded motion parameters of the manned model test can be compared with the results of the simulation of the human controlled manoeuvre.

By this technique it is not possible to achieve good results regarding the turning ability, yaw checking or course keeping ability but by the fact that the exact human controlled manoeuvre is repeated by the simulator it is possible to use manned model test results for the validation of the modelling and simulation methods.

The explanation above is valid for both conventional propulsion and control systems and ACD. The differences are within manufacturing of the control devices in the scale of the manned model and the modelling of the performance if the devices within the simulator.

In general the common scaling problems for model tests have to be considered, because model tests are carried out on the basis of Froude’s law and for the scaling of the flow at propellers and rudders Reynolds law has to be applied. The larger the model scale is, the bigger is the scaling discrepancy between Froude’s and Reynolds law. While the friction correction could be applied by e.g. an additional force using a wind propeller it is not possible to apply also corrections to the flow regime at the stern of the vessel including wake and slipstream.

4.5.3 Needs and possibilities to validate capabilities:

Two types of data can normally be used for validation purposes. The first is the full scale measurement data (e.g. in sea trials or specially-targeted full scale measurements). The second and the main source is the experiment data obtained in various model tests.

4.5.3.1 Validated capabilities of existing modelling methods

To a large extent the following simulation capabilities of mathematical model based methods can be appropriately validated:

Manoeuvring
(1) Turning circle manoeuvre
(2) Zig-zag manoeuvre with helm angle 10º/ 10º and 20º/ 20º to both sides
(3) Full astern stopping manoeuvre

The above simulation capabilities are demonstrated in the versatile thematic reports These capabilities are the most fundamental components of a simulation program for manoeuvring simulations in still water.

Seakeeping
(1) Parametric roll motion,

Prediction of loads
(1) Manoeuvring induced side loading

4.5.4 Further needs of validation data

At present the following simulation capabilities are more difficult to achieve and validate, largely due to lack of relevant experimental and full scale data.

(1) Response under extreme steering
(2) Manoeuvring in ice
(3) Slamming effect

Therefore, there is an urgent need of model test data in these areas for ships fitted with pods. Furthermore, it is noted that the data that can be used to validate detail flow field results (e.g. flow separation at large azimuthing angle) obtained from RANS computations is very scarce due to the complexity involved in measurement. The flow field data is needed for validating RANS computations.

5. MODELLING METHODOLOGY SELECTION TABLES.

5.1 Modelling

5.1.1 General

An ACD is modelled as a source of force, which is variable in direction and magnitude. The input is given from the controlled by an azimuthing handle with a lever for setting the engine order. Details to these devices can be found in deliverable D2.5 .

The modelling itself is the mathematical formulation of the force depending on the input values which will be applied at the point where the ACD is mounted in the vessel. This force can be used to generate forward thrust, lateral thrust and a combination of both depending on the settings of the input devices. The yaw momentum is calculated using the lever of the mounting position to the centre of gravity.

Depending of the data available for the setup of the mathematical model of an ACD it can be subdivided in three stages of complexity: simple, advanced and sophisticated.

5.1.2 Main external parameters

Additionally the quality of the mathematical model is influenced by the number of external parameters which are considered in the final force vector calculated. These influences are e.g.:

A) Alteration of the thrust due to the ships velocity

When a ship moves forward the thrust is influenced by the ships speed. In motion straight ahead the thrust is reduced. In steering conditions the thrust vector is deflected due to the flow and does not point into the direction ordered by the control.

B) Reduction of the flow at the stern due to the wake

Due to the hull form of a ship the flow is decelerated at the stern. ACD mounted at that position have an inflow velocity which is less then the ships speed.

C) Consideration of the flow direction in yaw motions at the position of the ACD

When a ship turns a significant lateral flow component can be observed a at its stern. This oblique inflow influences the performance of an ACD and finally it manoeuvring capabilities.

D) Reflection of the thrust from skegs and fins

The presence of the hull and additional appendages like skegs and fins disturb the free flow of an ACD. There is a significant reduction of manoeuvring force to be expected, when the slipstream of the ACD hits appendages and also the hull.

E) Interaction of multiple ACD

When two or more ACD are installed in vicinity of each other their thrust may be superimposed to the inflow or the slipstream of the others. In most cases the total efficiency is reduced, in some cases it may be improved.

5.2 Future Activities

Having in mind complexity and novel features of contemporary horizontal propulsors some consistent activites seem to be necessary in the nearest future. They to be organized in the logical way making use of the present achievements as deeply as possible. In order to received the reliable scope of results they should be devided into two main groups:

5.2.1 Testing

Testing of new solutions to be done mainly be means hydrodynamic experiments, however use of CFD tools is getting more useful and reliable. The tested models to be equipped with their specific and novel elements corresponding with elaborated respective parametric models taking into account external parameters as widely as possible . Indispensable alterations of these elements should be satisfactory for due subsequent analyses and generalizations.

5.2.2 Validation

Validations of elaborated mathematical model is the most important part of their assessment. Usually it is done with use of full scale ships results assuming necessary identities between a ship and an elaborated models. In case of ships propelled by novel horizontal propulsors there are serious difficulties resulting from very limited offer of respective ships. It can be replaced by results of manned model investigations in which the tested model are large enough.
The typical model tests can deliver majority of necessary data but due to their different sizes the received results demand individual validations taking into account the scale effect and uncertainty of applied procedures.