Intuitive operation
and pilot training
when using marine
azimuthing
control devices

AZIPILOT

Report Title:

Deliverable 1.2:

Review of existing modelling & test methods for azimuth devices

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EXECUTIVE SUMMARY

The aim of this task is to review existing modelling and test methods for azimuthing control devices. The objectives are to both document existing methods and establish the extent to which these methods are valid. The main points for consideration include:

1. *Survey steady-state testing methodologies.*
2. *Survey of ability to model azimuthing control device-to-hull interactions.*
3. *Survey of ability to model interactions between multiple azimuthing control devices.*
4. *Discuss propeller and nacelle interactions including scaling issues and gap effects.*
5. *Discuss effects on propeller working point and off-design conditions.*
6. *Explore extent of current validation.*
7. *Explore the need for dynamic testing methods*.

All necessary works started with steady state testing methodologies. The main source of this knowledge was the basic method of W. Froude elaborated in 19^{th} century and its further modifications. On this example it was possible to recognize all factors influencing propulsive predictions and to select main stages of model tests together with their limitations and necessary approximations. One of the most important topics was the scale effect resulting from totally different Reynolds numbers levels during model scale and sea trials investigations.
Methodology of manoeuvrability model tests is based on IMO recommendations. IMO resolution MSC.137 (76) determines all conditions, assumptions and criteria concerning this group of tests.
Since, typical podded propulsor is composed from a relatively big nacelle with an electric motor inside being suspended below the ship hull with use of rotating hydrofoil, azimuthing propulsors have introduced a lot of new qualities to the hydrodynamic modelling it was obligatory to explore all new interactions between propulsor elements so as to take them into account in newly elaborated mathematical models and algorithms.
That is why the following interactions were taken into account:

- Control device to ship hull ;
- Among multiple control device;
- Podded propeller to pod housing;
- Effects on propeller working point;
- Off design conditions.

Moreover, the extent of current validation was reviewed and analyzed.
Apart from direct experimental topics, a role of ITTC was presented in scope of model testing integrations, elaborated methods, procedures and recommendations.
The gathered information can be useful in taking into account these new interactions to enrich and widen presently used methodologies.

1. INTRODUCTION

1.1 General

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.

1.2 Activities of the ITTC – the Specialist Committee on the Azimuthing Podded Propulsion

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 origin of the ITTC was the meeting of the International Hydro-mechanical Congress held in Hamburg in 1932. One of the consequences of this meeting was the decision to maintain the activities through regular meetings (initially on alternant years; now every three). To support activities the ITTC has a number of General Committees (Resistance; Propulsion; Manoeuvring; Seakeeping; Ocean Engineering), which are maintained to investigate new issues in their respective fields. In addition, the ITTC supports a number of Specialist Committees, tasked with investigating topical issues. One such Specialist Committee, 'The Specialist Committee on Azimuthing Podded Propulsion', was established for both the 24th and 25th terms of the ITTC. As the name suggests, this Specialist Committee was tasked with investigating issues related to azimuth pod drives and the methods and subtleties of hydrodynamic testing thereof.
The contents herein summarise the reliant activities reported by the above Committee. Also, additional comments are included regarding possible methods for dynamic testing.
The recommendations of the 23rd ITTC guide the activities of the 24th. In summary, the main recommendations from the 23rd ITTC suggested making improvements to the procedures for podded propulsor testing and extrapolation and procedures for carrying out cavitation testing. It was also recommended that guidelines should be established for extrapolation to full-scale. In addition, reviews should be made regarding the impact on off-design conditions to loads and stability and the impact on the IMO manoeuvring criteria.

2. STEADY STATE TESTING METHODOLOGIES

2.1 Resistance and Self Propulsion Tests

2.1.1 General information

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.

2.1.2 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.

2.1.3 Recalculation methods of resistance and self propulsion tests

2.1.3.1 Resistance tests:

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.

2.1.3.2 Self propulsion tests:

Since model tests are executed at Reynold's 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

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

2.1.4 Typical testing methodology of podded vessels

2.1.4.1 Measured values during model tests:

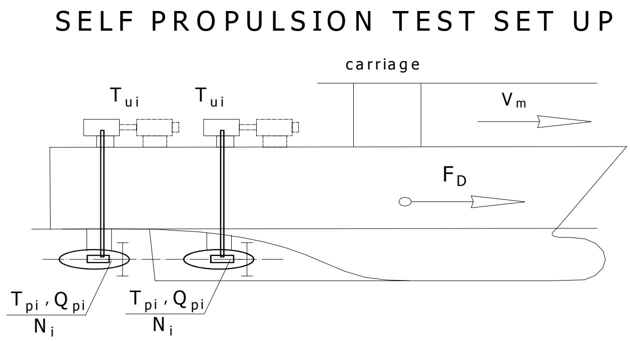


Fig. 2.1 Scheme of measured values

2.1.4.2 Procedure of podded vessel model tests - ITTC 23 recommendations:

- scheme of subsequent steps:

Step 1
Pod unit, as propulsion system, composed from: nacelle, strut, podded propeller, propelled directly by internal electric motor

Step 2
Resistance test of bare hull without pod propulsors:
Measured values: V_M, R_{TM}

Step 3

Measurements of podded propulsor performances in „open water" conditions, including podded propeller thrust

Measured values : V_{aM}, n_M, $Q_M^{pod\text{-}0}$, $T_M^{pod\text{-}0}$, $T_M^{pp\text{-}0}$

↓

Step 4

Measurements of podded propeller in „open water" conditions

Elaboration of characteristics: $K_{TM}^{0}(J)$, $K_{QM}^{0}(J)$

↓

Step 5

Determination of pod thrust as difference between podded propeller thrust and its housing resistance:

$T^{pp\text{-}0} - D_T^{housing.}$

↓

Step 6

If podded propeller thrust can not be measured (step 3), wake coefficients are determined on torque identity basis and corrected to the full scale. They are used afterwards for determination of the podded propeller work point

J_{PP}

↓

Step 7

Correction of propeller characteristics to ship full scale, taking into account friction losses on podded propeller blades :

ΔK_T^{blade}, ΔK_Q^{blade}

↓

Step 8

Determination of pod housing resistance (step 3), (step 5) or (step 6), if necessary:

$D_T^{housing.}{}_M = T^{pp\text{-}0}{}_M - T^{pod}{}_M$

↓

Step 9

Application of respective method for pod housing resistance correction to ship full scale

$\Delta K_T^{housing.}$

↓

Step 10

Pod propulsor performances (step 3) are added to scale effect corrections (step 7) and (step 9), to receive pod open water characteristics in full scale:

$$K_{TS}^{pod\text{-}0} = K_T^{pod}{}_M + \Delta K_T^{blade} + \Delta K_T^{housing.}$$

$$K_{QS}^{pod\text{-}0} = K_Q^{pod}{}_M = \Delta K_Q^{blade}$$

Step 11

Self propulsion test with pod propulsors , friction losses correction force F, taking into account pod housing resistance scale effect (step 9).

Measured values: V_M, n_M, $Q^{pod}{}_M$, $T^{pod}{}_M$ i $T^{pp}{}_M$, if possible

Step 12

Determination of interaction coefficients: hull – pod propulsor :

$$t_S = t_M = (\sum T^{pod}{}_M - R_{TM}) / (\sum T^{pod}{}_M)$$

$$w_{TS} = w_{TM} = (J_v - J^{pod}{}_T) / J_v$$

Where $J_v = V_M / (n_M D_M)$ from self propulsion test, and

$J^{pod}{}_T$: from pod open water tests on thrust identity basis:

$$w_{QS} = w_{QM} = (J_v - J^{pod}{}_Q) / J_v$$

Where $J^{pod}{}_Q$: from pod open water tests on torque identity basis:

$$\eta_H = (1\text{-}t_S) / (1\text{-}w_{TS})$$

$$K_{TS}^{pod} = K_T^{pod}{}_M + \Delta K_T^{housing} + \Delta K_T^{blade}$$

$$\eta^{pod\text{-}0}{}_T = (J^{pod}{}_T / 2\pi)(K_T^{pod} / K_{QT})$$

where $K_T^{pod} = K_T^{pod\text{-}0}$ i

K_{QT} from pod open water test (K_Q at $J^{pod}{}_T$)

$$\eta_D = P_E / P_D$$

$$\eta_R = \eta_D / (\eta^{pod\text{-}0}{}_T \ \eta_H) = K_{QT} / K_Q^{pod}$$

Where K_Q^{pod} taken from self propulsion test, and K_{QT} from pod open water test

(K_Q at $J^{pod}{}_T$).

Step 13

Podded propeller revs (n_S) and delivered power (P_{DS}) are determined with use of full scale advance coefficient (J_{TS}) and torque coefficient (K_{QTS}), read out from full scale pod characteristics.

Where (J_{TS})is determined for each measurement point by adding demanded: ΔK_T^{blade}, $\Delta K_Q^{bladeand}$ and $\Delta K_T^{pod}{}_M$ to $K_T^{unit}{}_M$ and read out for K_{TS}^{pod} on full scale pod characteristics diagram.

$$\eta_S = (1\text{-}w_{TS}) V_S / (J_{TS} D)$$

$$P_{DS} = 2\pi\rho D^5 n^3{}_S K_{QTS} / \eta_R$$

For seatrials conditions respective corrections C_P-C_N to be applied :

$$N_{S\,trial} = C_N\, n_S$$

$$P_{DS\,trial} = C_P\, P_{DS}$$

2.1.5 Scale effect

2.1.5.1 General approach:

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} :

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

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

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

where: ρ - water density

n – propeller revs

D – propeller diameter

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

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

where:

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

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

2.1.5.2 Scale effect in CTO methodology (Welnicki 2003):

Generally, characteristics of a pod unit are presented in dimensionless form as an equivalent propeller K_T^{unit};K_Q^{unit} = f (J) with the podded propeller size. Corrections for blades are determined as : ΔK_T^{blades} i ΔK_Q^{blades} = f (J). Pod housing influence is taken into account as correction $\Delta K_T^{housing}$.

$$K_T^{unit} = K_T^{o.w.\ tests} - \Delta K_T^{blades} + \Delta K_T^{housing}$$

$$K_Q^{unit} = K_Q^{blades} - \Delta K_Q^{blades}$$

The correction, taking into account presence of the pod housing, is limited to a pod housing surface strip located within the podded propeller race – see figure 2.2 below:

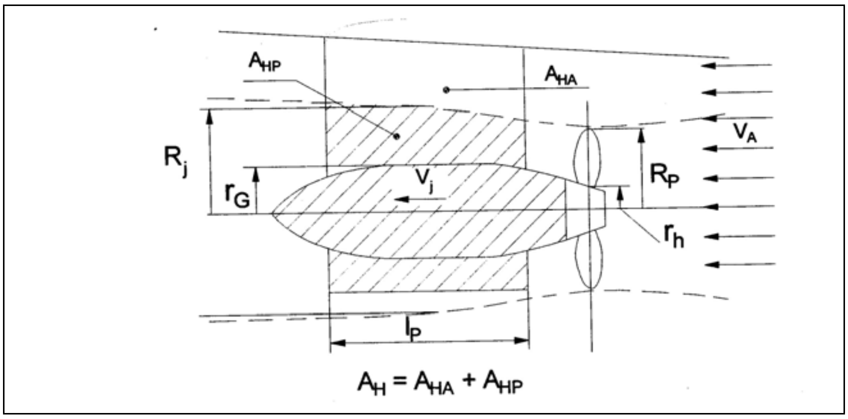


Fig. 2.2 Scheme of pod unit flow

The surface area of his strip and local velocities can be calculated in the following way:

- flat plate friction coefficient acc. to ITTC-57 :

$C_F = 0.075 / (\log Re - 2)^2$

- correction $\Delta K_T^{housing}$:

$\Delta K_T^{housing} = (C_{FOHM} - C_{FOHS}) [Kb + (1-b)] A_{HM} J^2 / 2D_M^2$

where:
C_{FOHM} i C_{FOHS} are friction coefficients for the pod housing and Reynolds numbers determined according to formulae:

$R_{nH} = l_p \; V_A K^{0.5} / \nu$

A_{HM} – pod housing surface area

A_{HPM} – pod housing surface area inside of podded propeller race

$b = A_{HPM} / A_{HM}$ – surface areas ratio

D_M – podded propeller diameter

$K = (V_{jM} / V_{AM})^2$ coeff. determined by experiments

$V_{jM} = V_{AM} (1 + C_{TM})^{0.5}$ – velocity of propeller slipstream

$C_{TM} = T_{UM} / (1/2 \, \rho_M V_{AM}{}^2 \, \pi R_{PM}^2)$ – coeff. of the propelled disc thrust load

$R_{jM}^2 = ½ [1/ (1 + C_{TM})^{0.5} + 1](R_{PM}^2 - r_{hM}^2) + r_{GM}^2$ – mean radius of propeller slipstream

Scale effect is taken into account as thrust corrective component ΔT_2 :

$$\Delta T_2 = \Delta R_{Pod} = (C_{FOHM} - C_{FOHS}) V_F^2 \, A_H \, \rho/2$$

$$\Delta T_2 = (C_{FOHM} - C_{FOHS}) \, (V_j^2 \, A_{HP} + V_A^2 \, A_{HA}) \rho/2$$

and thrust correction ΔK_2 :

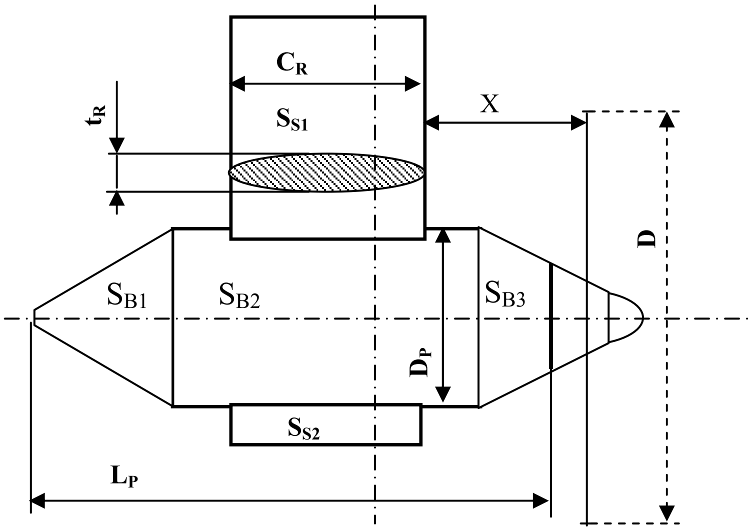
$$\Delta K_2 = (C_{FOHM} - C_{FOHS})\,(V_j^2\ A_{HP} + V_A^2\ A_{HA})\frac{\rho}{2\rho D^4 n^2}$$

where:

C_{FOHM} - friction coeff. acc. to ITTC-57 for pod model

C_{FOHS} - friction coeff. acc. to ITTC-57 for full scale pod

2.1.6 Extrapolation of resistance characteristics of propeller housing (ITTC,2008)



$\boldsymbol{S}_{BODY} = S_{B1}+S_{B2}+S_{B3}$

$\boldsymbol{S}_{STRUT} = S_{S1} + S_{S2}$

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

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

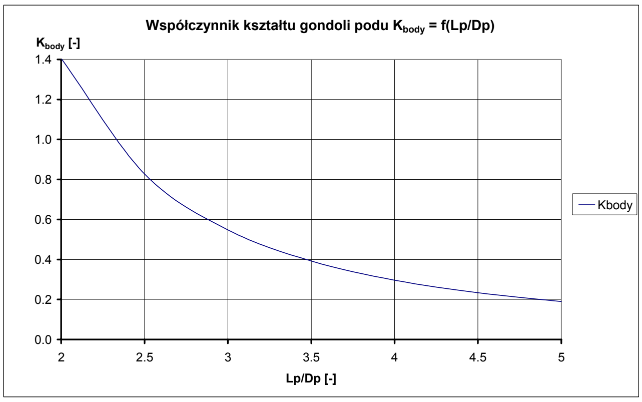


Fig. 2.3 Pod body form coeff. $k_{BODY} = f(L_P/D_P)$

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

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

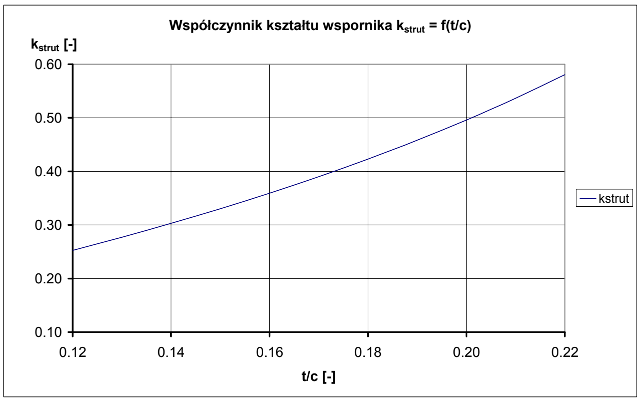


Fig. 2.4 Strut form coefficient $k_{STRUT} = f(t/c)$

$$V_{INFLOW} = V_A (1 + C_T)^{0.5}$$ - induced speed at propeller disc

$$C_T = \frac{T}{0.5 \rho V_A^2 A_P}$$ - coeff. of propeller disc thrust load

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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 Manoeuvrability Tests

2.2.1 IMO manoeuvrability standards (IMO,2002)

2.2.1.1 General

IMO manoeuvrability standards, started in the twentieth, have been adopted on Dec.4 2002 as the **RESOLUTION MSC. 137 (76).** They were intended to create tools for uniform assessment of the manoeuvring performance of ships and to assist those responsible for the design, construction, repair and operation of ships. However, it should be noted that the Standards were developed for ships with traditional propulsion and steering systems i. e. including shaft driven ships with conventional rudders. In such circumstances, it was assumed the Standards to be periodically reviewed and updated.

In order to evaluate manoeuvring performances of a new ship at the design stage, it is necessary to predict the ship manoeuvring behaviour on the basis of main dimensions, lines drawings and other relevant information available at the design stage.

There is variety of methods for prediction of ship manoeuvring behaviours at the design stage, varying in the accuracy of predicted manoeuvres.

In the aspects of accuracy, model tests have been considered for years as the most reliable prediction method. However, it can be said that accuracy requirement have been more lenient in this area than in other areas of ship model testing. It mainly resulted from absence of manoeuvring standards. The feedback of full scale trial results has generally been less regular in this area than in case of speed trials. Consequently, the correlation basis for manoeuvrability is therefore of a somewhat lower standard, particularly for hull forms which can present a problem with regard to steering and manoeuvring characteristics.

2.2.1.2 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.

- **<u>Manoeuvring tests with free running models</u>**
  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.

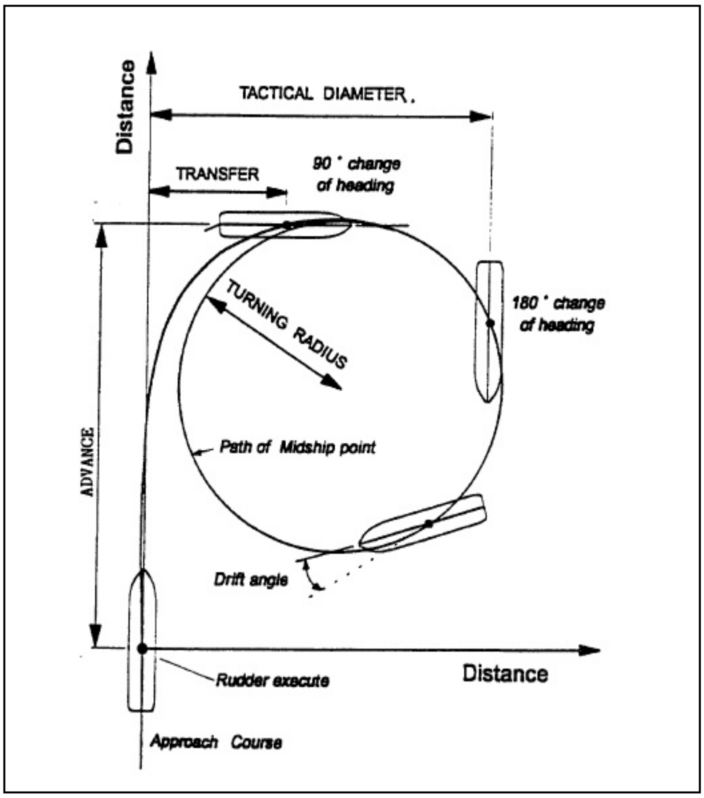
- **<u>Manoeuvring tests with captive models</u>**
  Captive model tests include oblique towing tests in long narrow tanks as well as "circling" tests in rotating arm facilities. Particularly such tests are performed with use of a Planar Motion Mechanism (PMM) which can produce any kind of motion by 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.

2.2.1.3. Standard manoeuvres and associated terminology

- <u>Conditions in which the standards apply:</u>
  - Deep, unrestricted water;
  - Calm environment;
  - Full load, even keel condition;
  - Steady approach at the test speed.

➢ <u>Turning tests</u>

Turning circle manoeuvre is the manoeuvre to be performed to both Starboard and Port with 35^o rudder angle or the maximum rudder angle permissible at the test speed, following a steady approach with zero yaw rate.
The test speed used in Standards is a speed of at least 90% of the ship's speed corresponding to 85% of the maximum engine output.

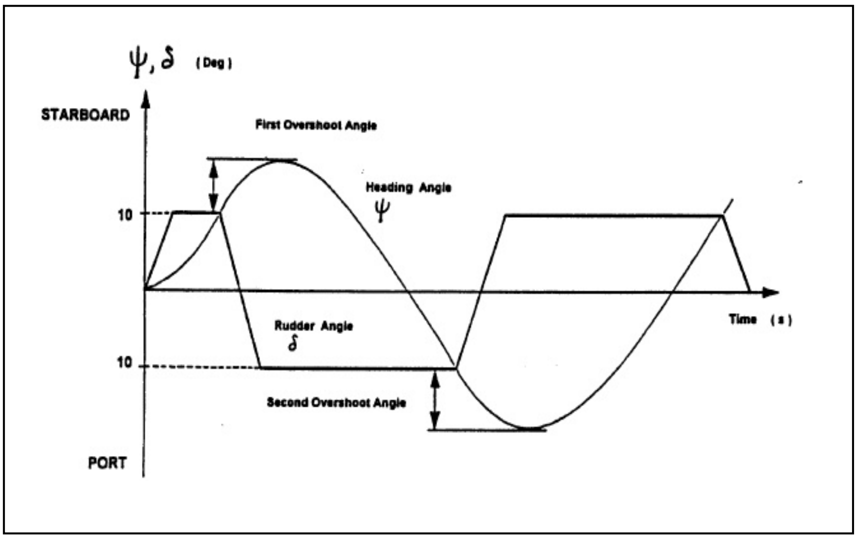


➢ <u>Zig-zag tests</u>

Zig-zag test is the manoeuvre where a known amount of helm is applied alternately to either side when a heading deviation from the original heading is reached.
The $10^o/10^o$ zig-zag test is performed by turning alternately by 10^o to either side following a heading deviation of 10^o from the original heading according to the following procedure:

- After a steady approach with zero yaw rate, the rudder is put over to 10^o to starboard or port (first execute);
- When the heading has changed to 10^o off the original heading, the rudder is reversed to 0^o to port or starboard (second execute);
- After the rudder has been turned to port/starboard, the ship continue turning in the original direction with decreasing turning rate. In response to the rudder, the ship turns then to port/starboard. When the ship reaches a heading of 10^o to port/starboard of the original course the rudder is again reversed to 10^o to starboard/port (third execute).

The first overshoot angle is the additional heading deviation experienced in the zig-zag test following the second execute. The second overshoot angle is the additional heading deviation experienced in the zig-zag test following the third execute.
The $20^o/20^o$ zig-zag test is performed similarly to $10^o/10^o$ manoeuvre but helm and heading values are respectively altered.

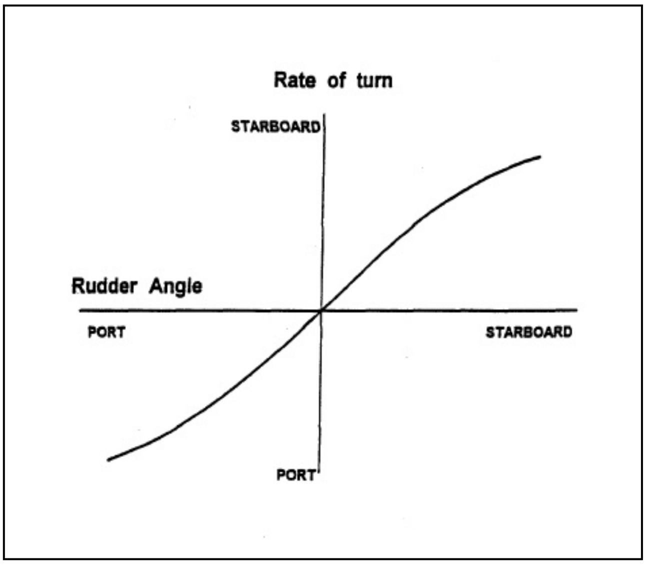


- <u>Spiral tests:</u>

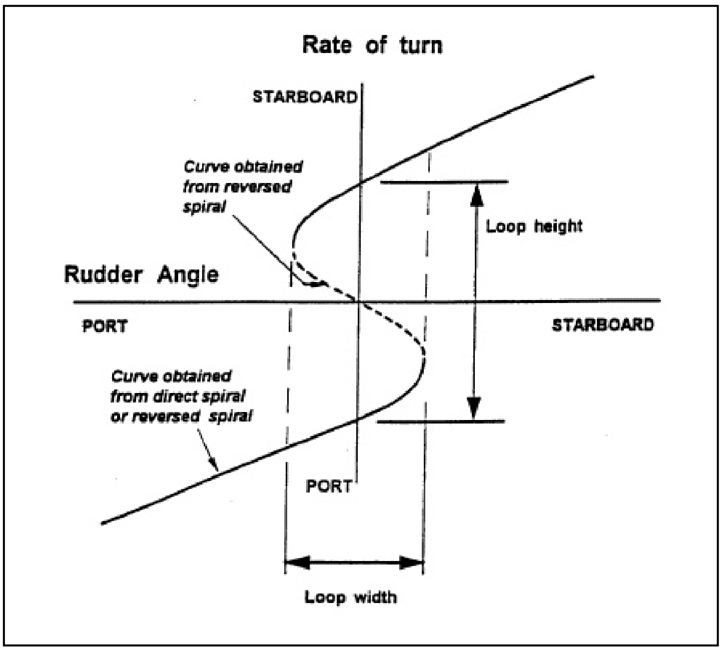
Spiral tests are performed so as to easily check course stability of a tested ship.
It is commenced with the steady approach with the assumed model speed.

- Direct spiral manoeuvre:
  The direct spiral manoeuvre is an orderly sequence of turning circle tests to obtain a steady turning rate versus rudder angle relation. It is a kind of testing in which various steady state yaw rate/rudder angle values are measured by making incremental rudder changes throughout a circling manoeuvre. Adequate time must be allowed for the ship to reach a steady yaw rate so that false indications of instability are avoided.
- Reverse spiral manoeuvre:
  In the reverse spiral test the ship is steered to obtain a constant yaw rate, the mean rudder angle required to produce this yaw rate is measured and the yaw rate versus rudder angle plot is created.
  The reverse spiral test may provide a more rapid procedure than the direct spiral test to define the instability loop as well as the unstable branch of the yaw rate versus rudder angle relationship.

A) Example of course stable ship:

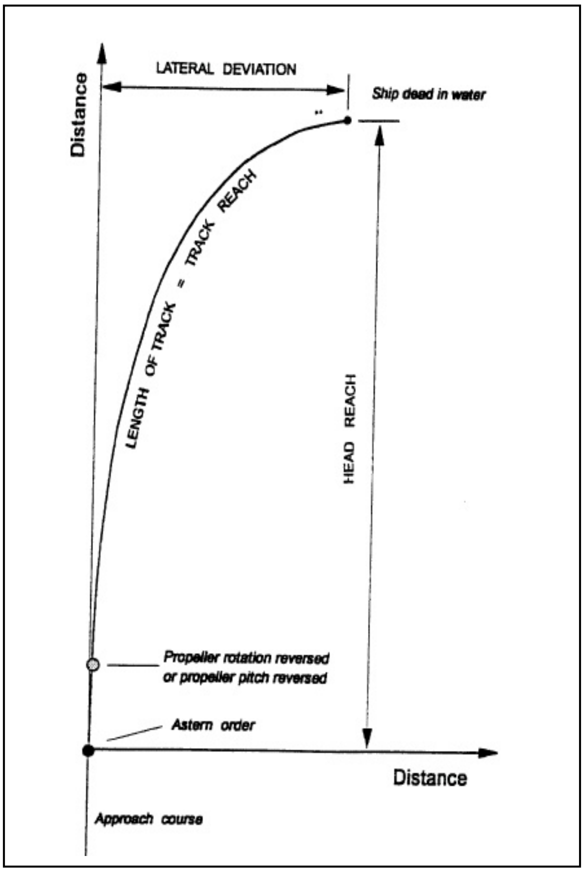


B) Example of course unstable ship:



➢ Stopping manoeuvres:

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. Track reach is the distance along the path described by the midship 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.



2.2.1.4 Criteria

The manoeuvrability of the ship is considered satisfactory if the following criteria are compiled with:

1) Turning ability:

The advance should not exceed 4.5 ship lengths and the tactical diameter should not exceed 5 ship lengths in the turning manoeuvre.

2) Initial turning ability:

With the application of 10^o 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^o fro the original heading.

3) Yaw checking and course keeping abilities:

- The value of the first overshoot angle in the $10^o/10^o$ zig –zag test should not exceed:
- 10^o if L/V is less than 10 sec;
- 20^o if L/V is 30 sec or more;
- (5 + ½(L/V)) degrees if L/V is 10 sec or more, but less than 30 sec.

Where L and V are expressed in [m] and [m/sec] respectively.

- The value of the second overshoot angle in the $10^o/10^o$ zig-zag test should not exceed:

- 25^o if L/V is less than 10 sec;
- 40^o if L/V is 30 sec or more;
- $(17.5 + 0.75(L/V)^o$, if L/V is 10 sec or more, but less than 30 sec.

- The value of the first overshoot angle in the $20^o/20^o$ zig-zag test should not exceed 25^o.

4) Stopping ability:

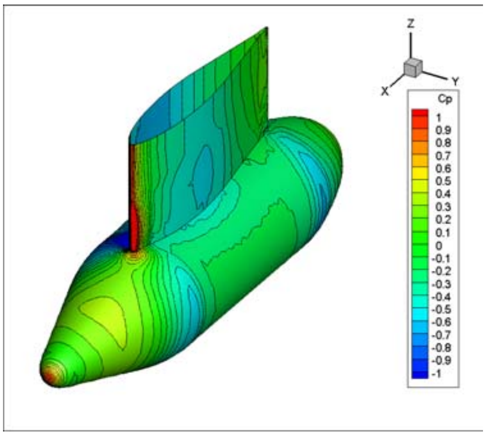
The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the administration where ships of large displacement make these criterion impracticable, but should in no case exceed 20 ship lengths.

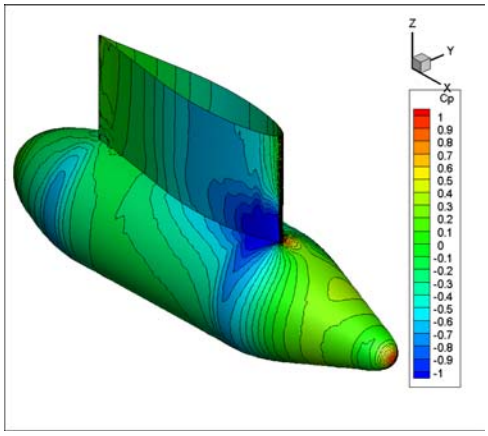
3. MODELLING OF AZIMUTHING CONTROL DEVICE-TO-HULL INTERACTIONS

3.1 Flow Specificity of Pod Unit (Kanar, Kraskowski, 2009)

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.

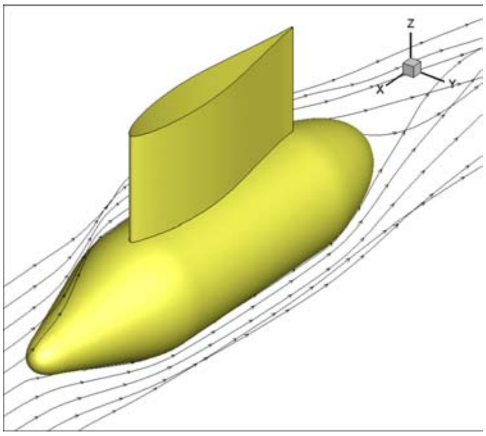
Pressure distribution along the POD body:

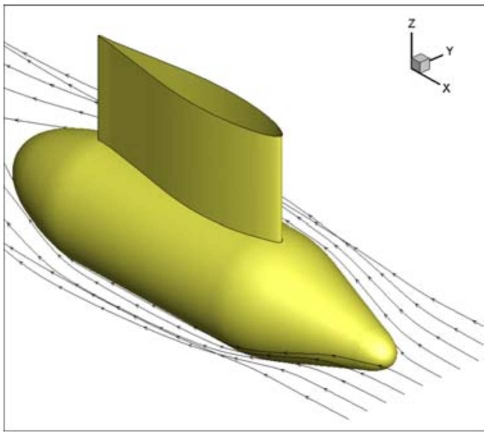




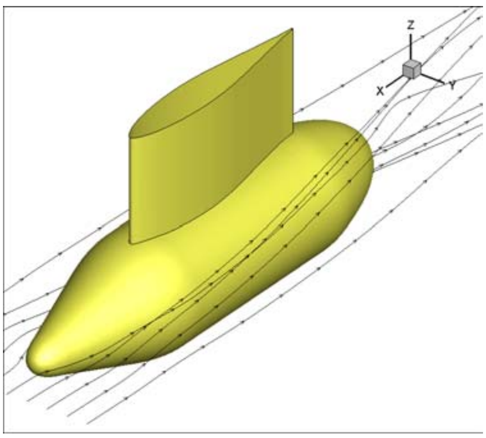
Streamlines:

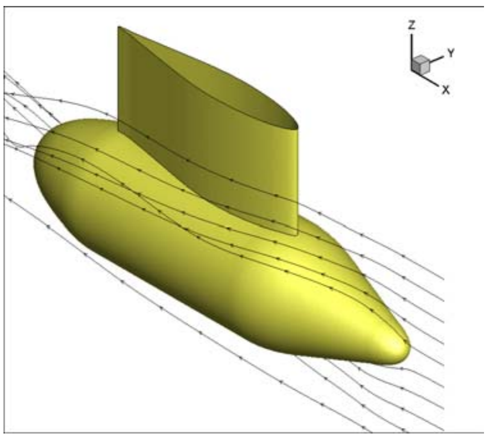
- part I:



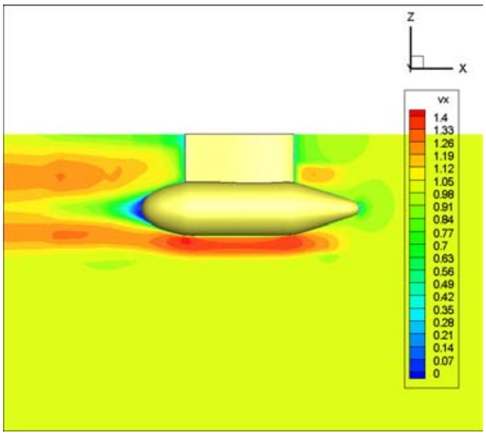


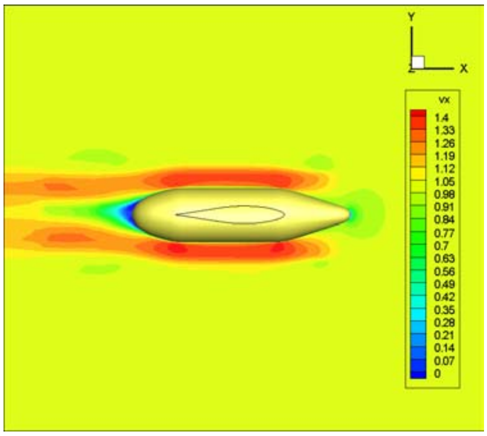
- part II





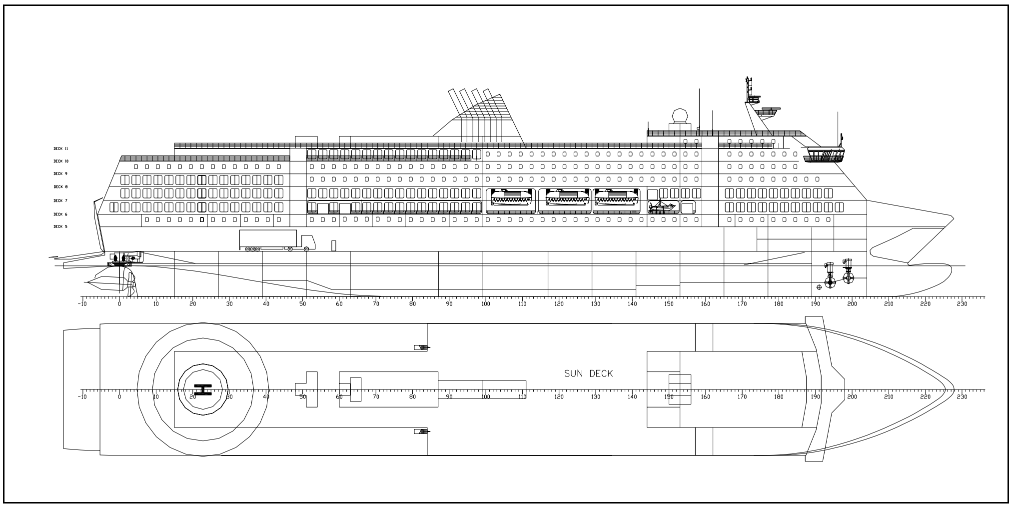
Local axial velocities distribution:





3.2 Pod Units Longitudinal Optimum Locations on Ropax Vessel

3.2.1 Subject Ropax vessel



L_{PP} = 172.20 m, B=28.4 m, T=6.60 m, V_S = 28.0 knt

The influence of longitudinal pod locations on resistance performances can be depicted with use of a medium size, fast Ropax vessel (Kraskowski 2009).

In two pods or more pods systems, relative big volumes of displacements, on the level of 2x100 cu.m are 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.

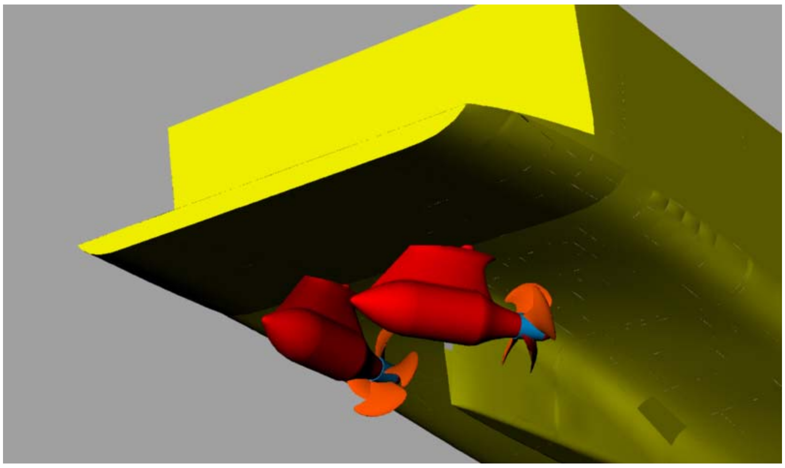


Fig. 3.1 Typical two pods arrangement

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.

3.2.2 Bare hull:

Some results received for a Ropax Vessel, during Optipod project realization (Kanar 2002), have been taken a reference system for further analyses and comparisons.

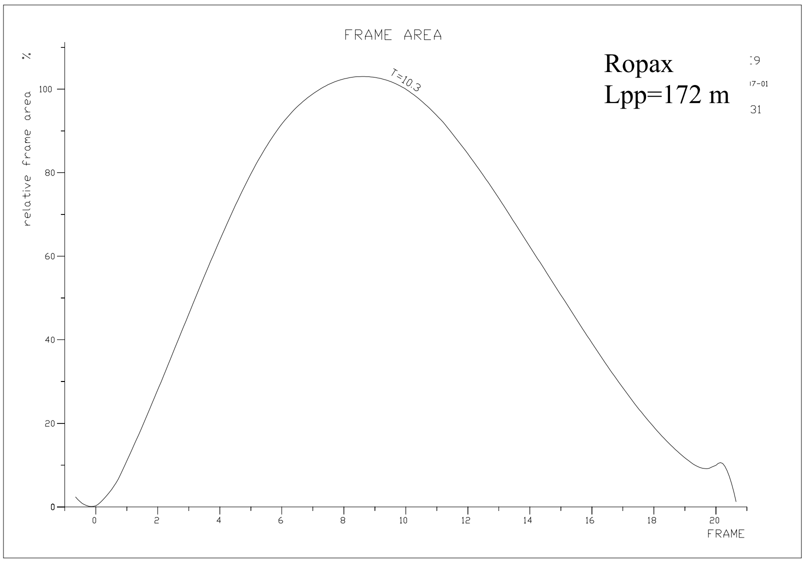


Fig. 3.2 Sectional area curve of analysed Ropax

Lpp=172.2 m, B=28.4 m, T=6.60 m, LCB= 80.1 m

Vs = 28.0 knt

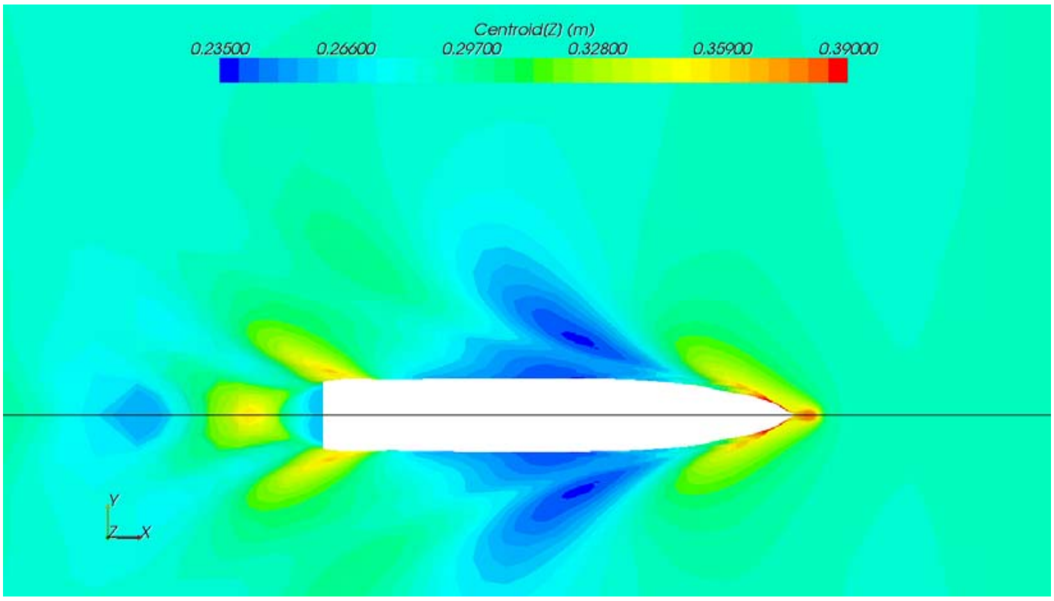


Fig.3.3 Wave system – bare hull

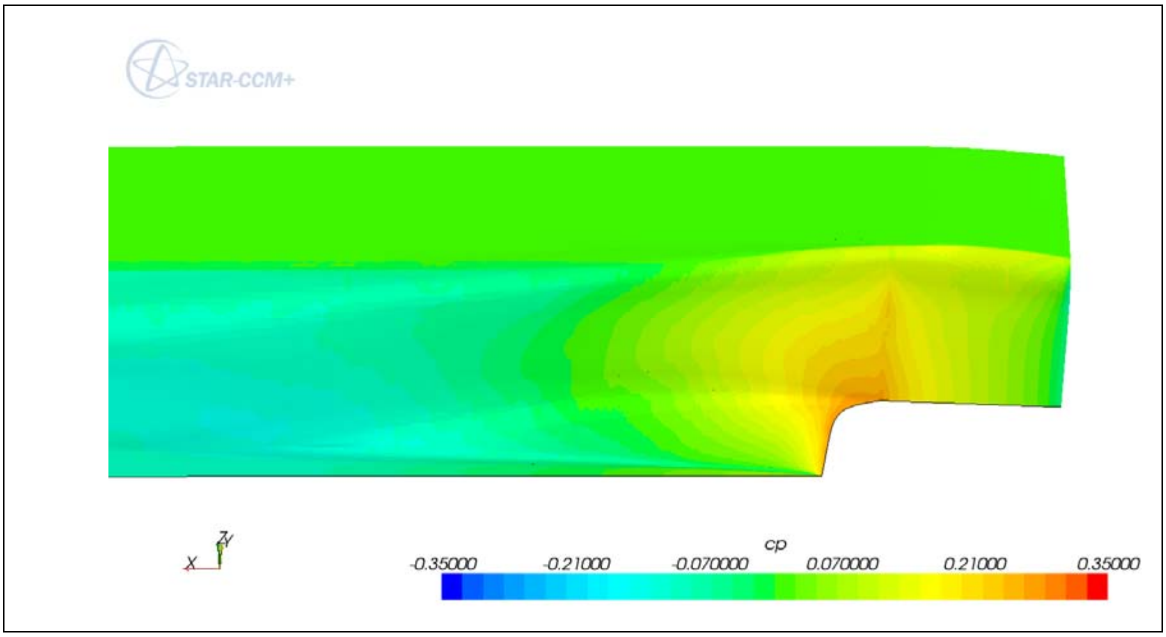


Fig.3.4 Pressure distribution in the afterbody region

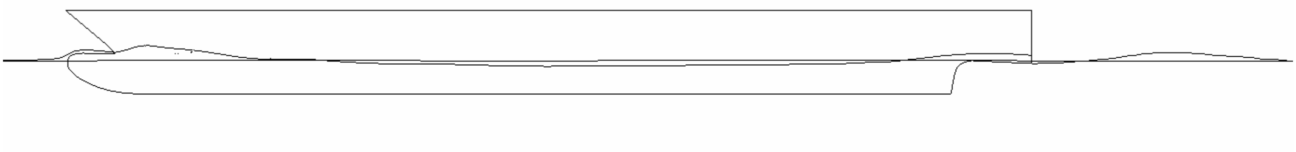


Fig. 3.5 Wave pattern along ship hull

1). Analyzed pods longitudinal locations :

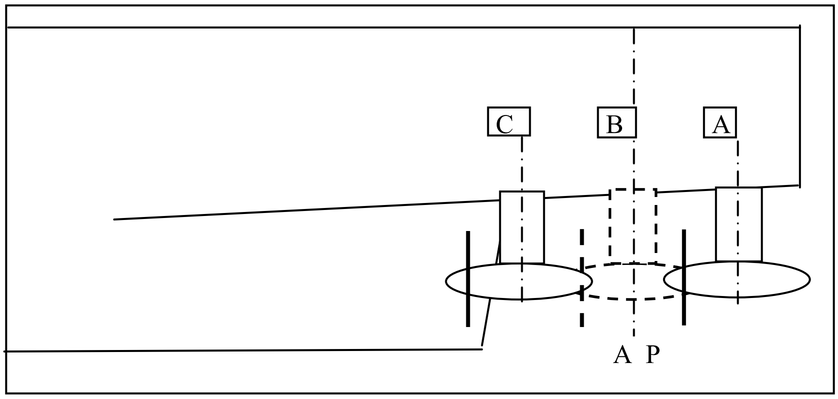


Fig. 3.6 Scheme of pods locations

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). Location of pod propulsors – Variant A: x = - 4.5 m
y = ± 7.1 m

- sectional area curve:

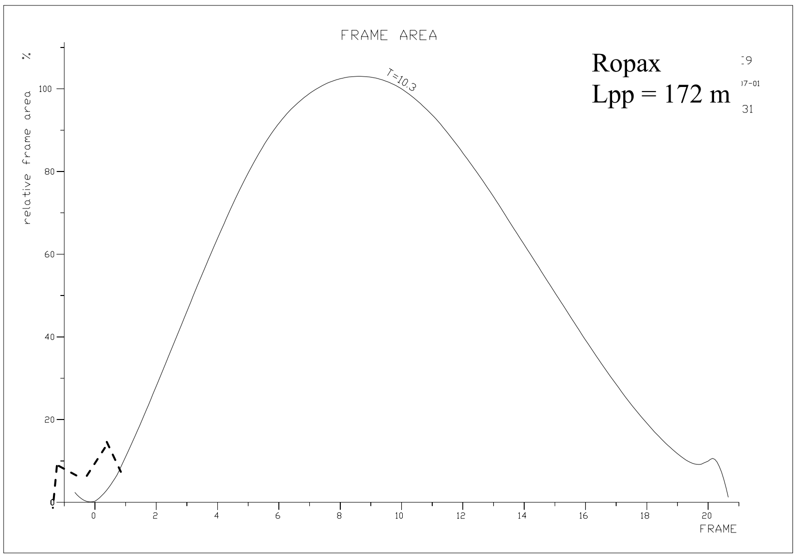


Fig. 3.7 Sectional area curve - Variant A

Lpp = 172.2 m B= 28.4 m T = 6.60 m LCB= -2.2%

Vs = 28.0 knt

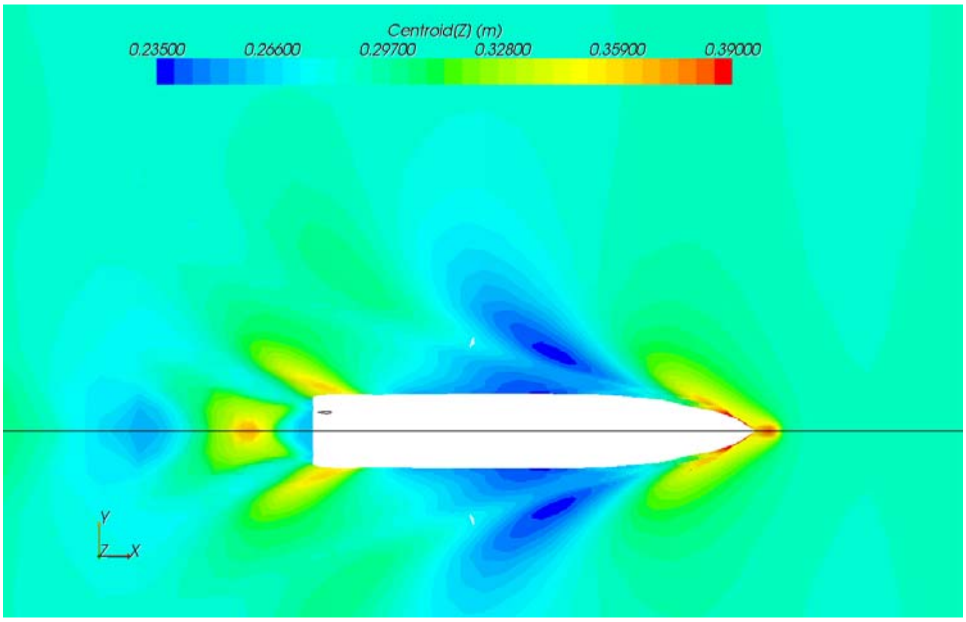


Fig. 3.8 Wave system - Variant A

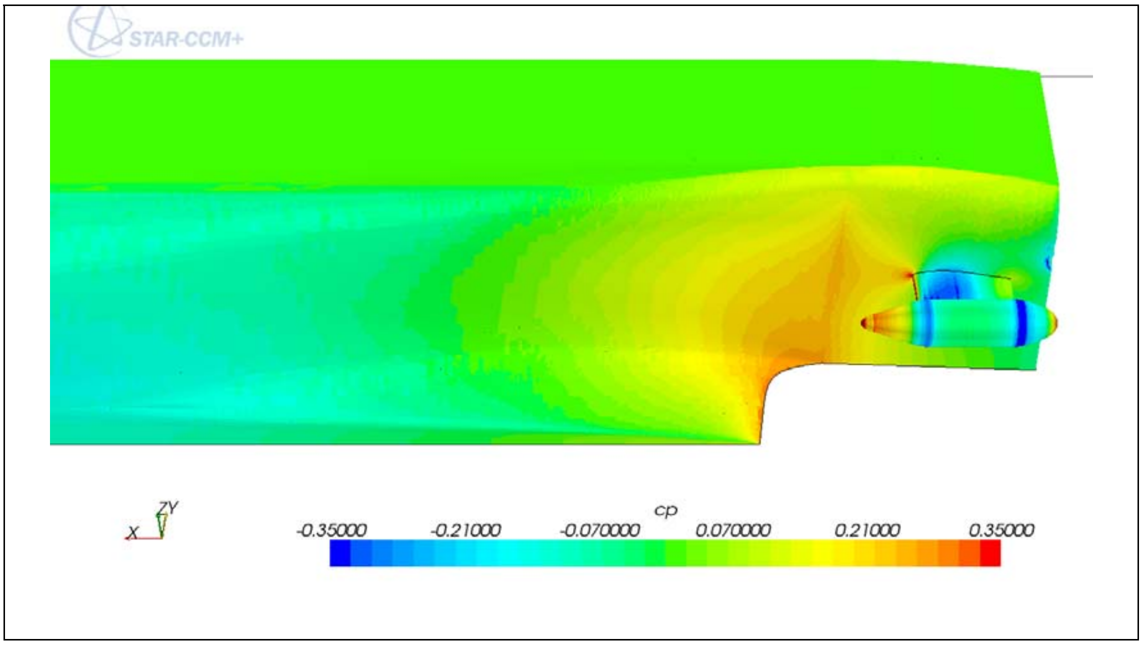


Fig. 3.9 Pressure distributions on hull - Variant A

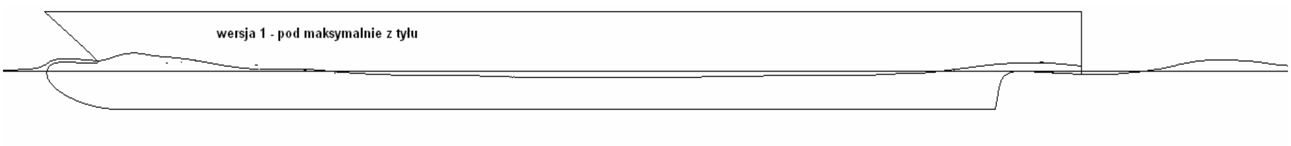


Fig. 3.10 Wave pattern along ship hull

3). Location of pod propulsors – Variant B : x = 0.0 m
y = ± 7.1 m

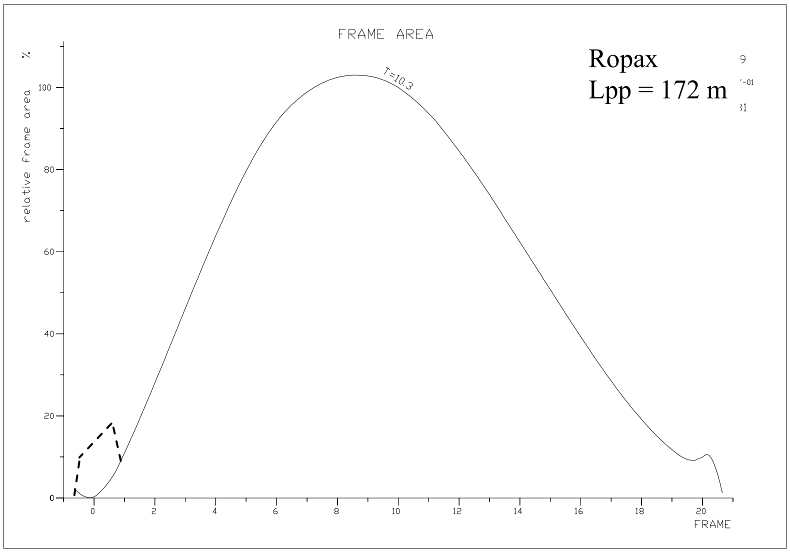


Fig. 3.11 Sectional area curve – Variant B

Lpp = 172.2 m B= 28.4 m T = 6.60 m LCB= -2.2%

Vs = 28.0 knt

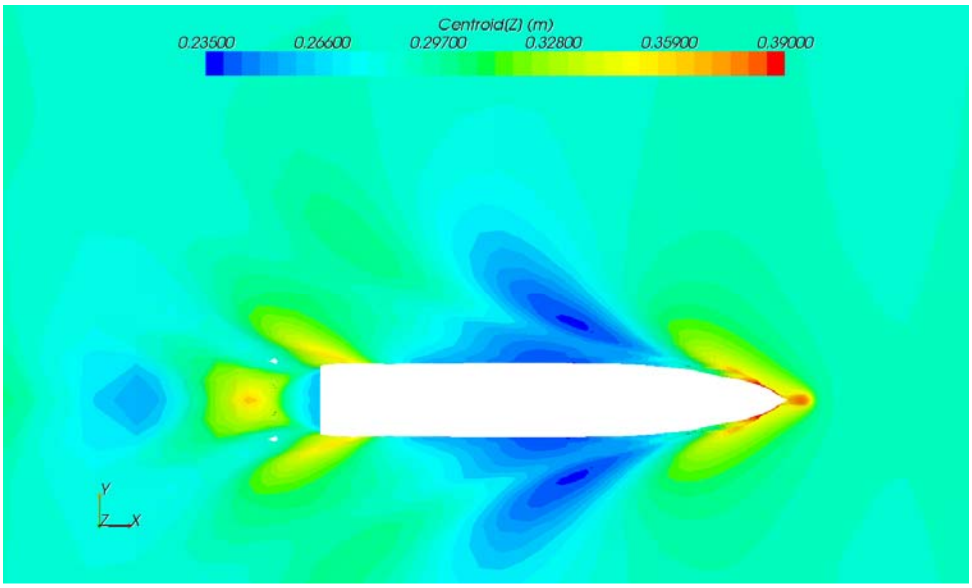


Fig. 3.12   Wave system - Variant B

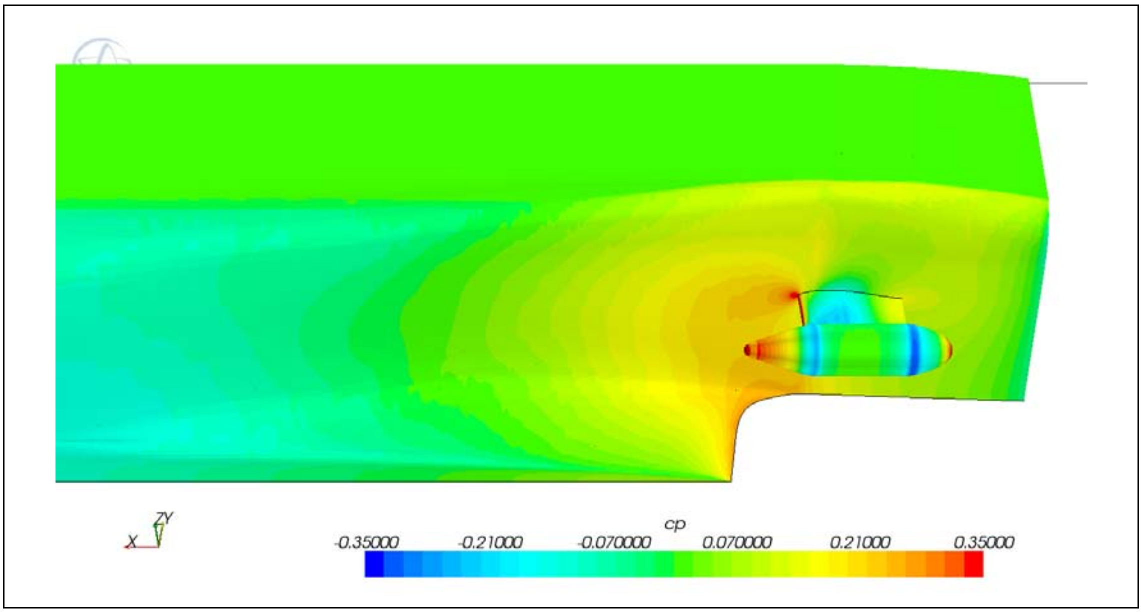


Fig. 3.13 Pressure distribution on ship hull – Variant B

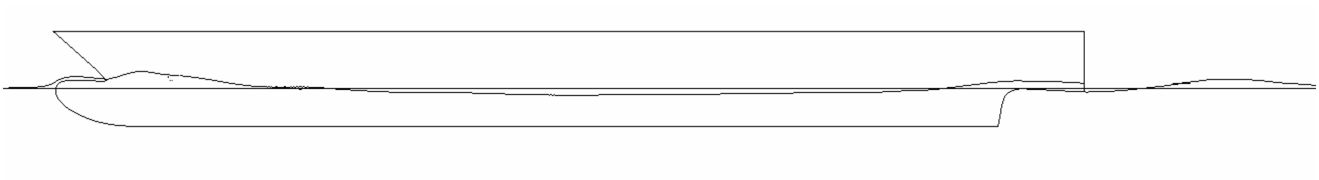


Fig. 3.14 Wave pattern along ship hull – wariant B

4). Location of pod propulsors - Variant C: x = + 5.5 m
y = ± 7.1 m

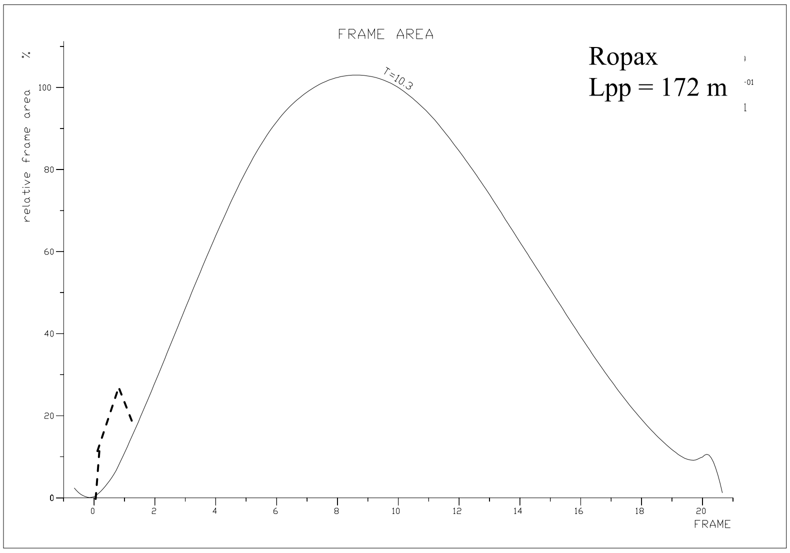


Fig. 3.15 Sectional area curve – Variant C

Lpp = 172.2 m B= 28.4 m T = 6.60 m LCB= -2.2%

Vs = 28.0 knt

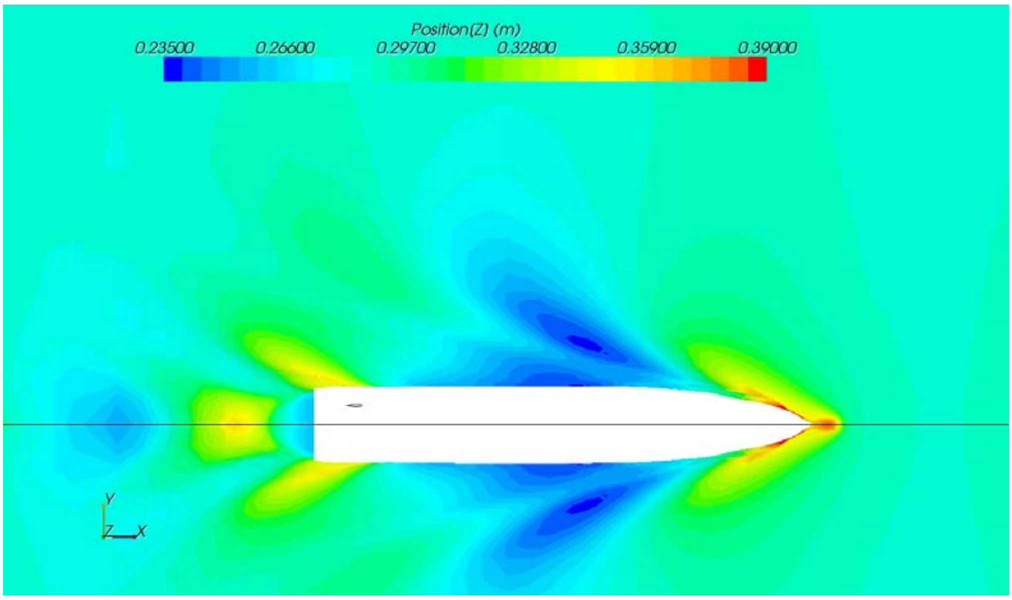


Fig. 3.16 Wave system– Variant C

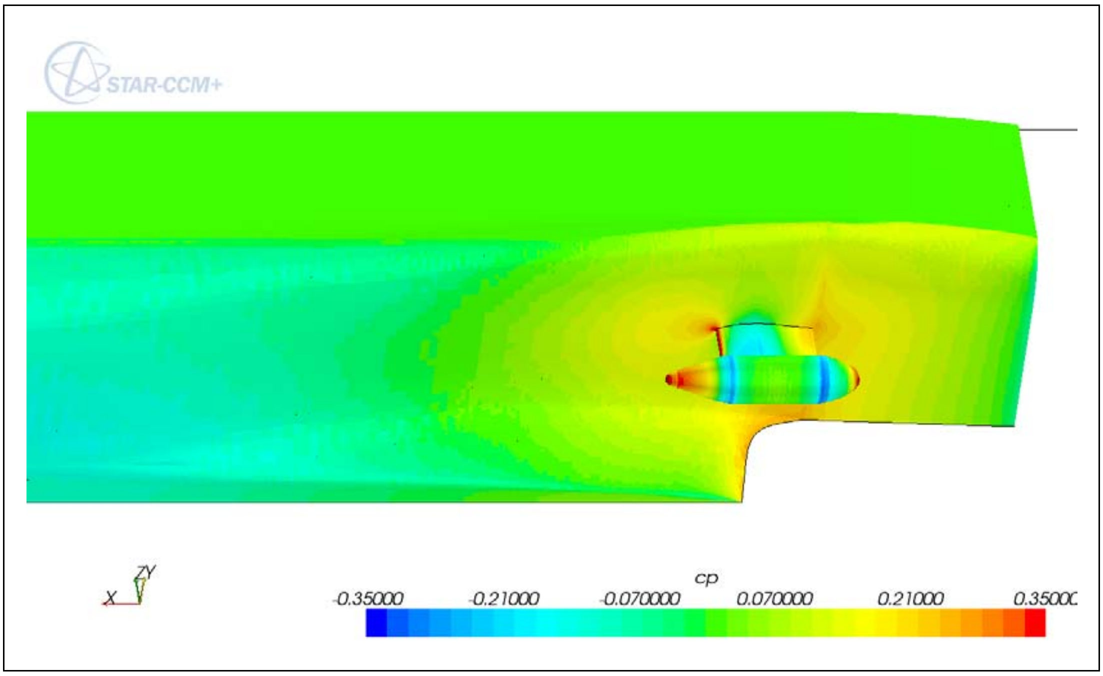


Fig. 3.17 Pressure distribution on ship hull – Variant C

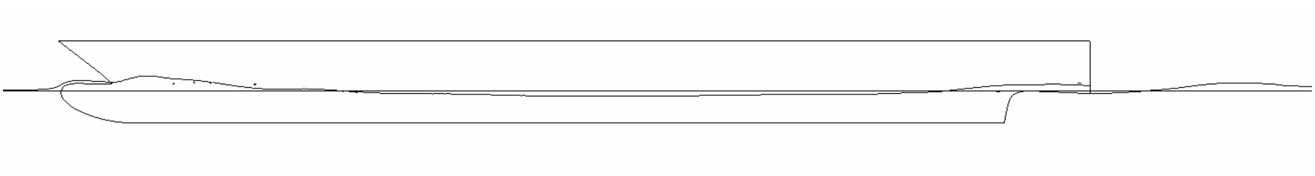


Fig. 3.18 Wave pattern along ship hull – Variant C

5). 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 %

4. INTERACTIONS BETWEEN MULTIPLE AZIMUTHING CONTROL DEVICES

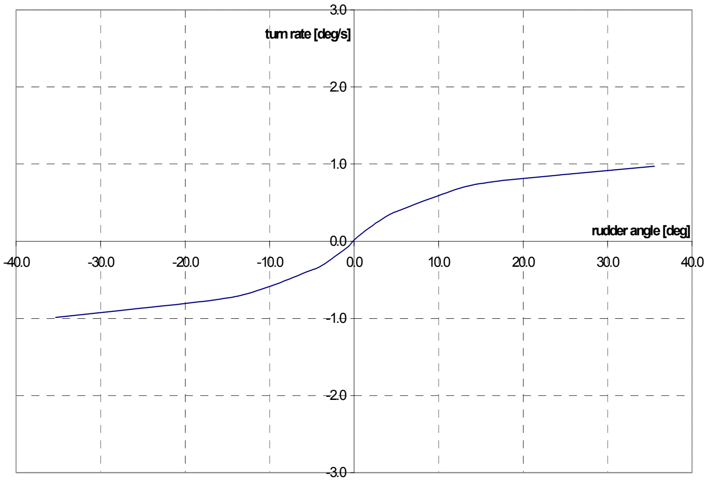
4.1 General Information

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.

4.2 Examples of Manoeuvrability Tests Results (Kanar, 2006)

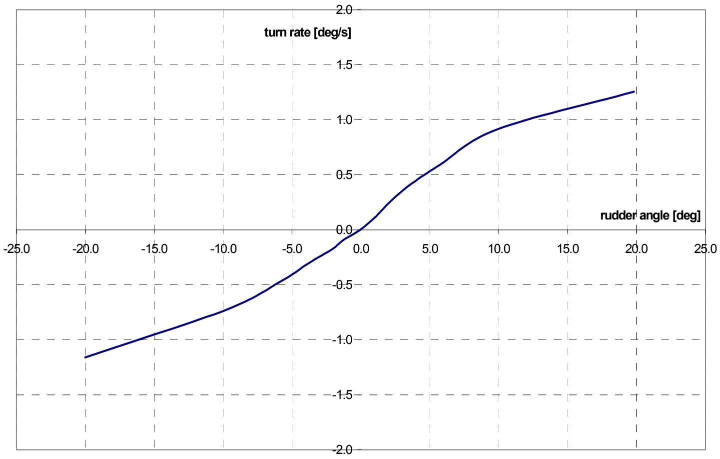
4.2.1 Tandem propellers plus twin pods

Direct spiral test:



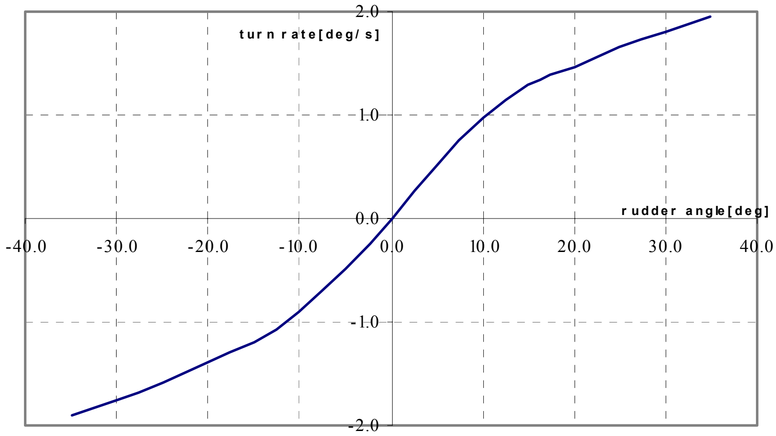
4.2.2 Four pod units – flapped units as steering devices

Direct spiral test:



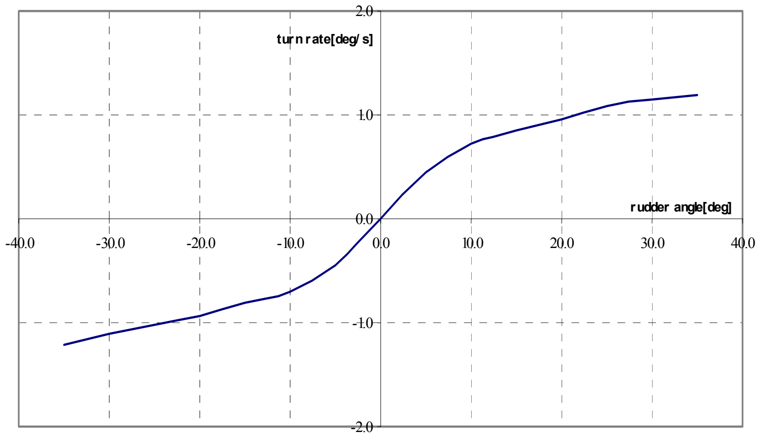
4.2.3 Two couples of pod units in CRP mode:

<u>Direct spiral test:</u>



4.2.4 All four pods working in steering mode:

Direct spiral test:



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

Steering devices configuration	Rudddder 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

4.2.6 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	-

5. PROPELLER AND NACELLE INTERACTIONS INCLUDING SCALING ISSUES AND GAP-EFFECTS

The ITTC Committee reports that after being established, a letter was received from a prominent pod manufacturer identifying a significant knowledge gap with regard to extrapolation to full-scale. 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.
The report gives a figure showing significant differences between pod-unit efficiencies for two different model basins. The letter claimed that these contradictions (a difference of up to 6.4% at design point) have a negative influence on the reliability of the concept as well as additional cost to the company. The letter concludes with a statement that the company is considering performing a comparative test campaign at several model basins using the same pod unit and propeller.

5.1 Propeller Open Water Tests

The Committee reports that the procedures for pod drive propeller open water tests are basically the same as the procedures for conventional open water tests. However, some aspects for propellers with strongly tapered hubs are not considered. It is reported that, for both puller- and pusher- type pods, the model-scale propeller hub should correspond to the full-scale propeller hub configuration. For a puller-type pod this means that the tapered full-scale hub and the corresponding cap geometry should be used. For the open water test set-up the aft fairing is also very important for puller-type pods – a non-faired transition from hub to aft fairing will introduce flow separation which will affect the measured propeller performance [an example is given in the report].
In the case where the hub rotates with the propeller, it is suggested that a separate pre-test should be performed on a similar set-up but with the propeller replaced by a dummy hub. This is considered necessary to correct the propeller open water test results for the effects on thrust and torque of the hub, hub-cap and the aft fairing. And from this, obtain the open water characteristics of only the propeller blades. Using this procedure means that all hub-cap, pod-housing and propeller gap effects are contained only in the pod open water characteristics – this is preferable for the propeller design. Specific characteristics of the propeller hub (hub gap effects; hub cone angle; hub cap geometry) are not included in the open water characteristics, but are included in the total pod open water characteristics, and are thus assigned as a total pod drive performance.
In the case where the hub does not rotate with the propeller, it is suggested that the same procedure must be adopted. In this case, the difference in gap effect between the pre-test and the actual open water test will be contained in the propeller blade open water characteristics.
Assuming negligible scaling error for the gap effects, the fixed hub method can provide useful knowledge of the effects of the pod-housing on the propellers performance. Generally speaking, the rotating hub method is considered preferable.

5.2 Pod Drive Open Water Test

The Committee reports that, pod drive open water tests are required when considering the complete pod unit. It is suggested that a basic device can be used to achieve a pod drive open water test incorporating a vertical shaft connected, via a right-angle gear box (or drive belt), to a horizontal propeller shaft, a dynamometer to measure propeller thrust and torque and a geometrically similar pod-housing. For the measurement of unit-thrust a force balance must be used on top of the vertical drive shaft.

A point of special concern on pod models is commented to be air leakage from the measuring frame along the vertical drive shaft of the pod. Pusher-type pods may be more susceptible due to propeller induced low pressure at the strut. Such air leakage may lead to propeller ventilation and should thus be prevented. This may be achieved by using a thin flexible latex hose to close off the opening between the measuring frame and the tube around the drive shaft. It is important that the Reynolds number of the flow around the pod models is high enough to avoid extensive laminar flow and even flow separation on the pod. In general, this requires the size of hull and pod models to be as large as possible. The use of turbulence tripping on the pod-housing helps to locally remedy a delayed flow transition, but is mostly of interest for pusher-type pods. For a puller-type pod, the propeller race will, in general, ensure an adequate turbulent flow over the housing.

The Committee report that, for pod drive open water tests, a special test set-up is required (a recommended configuration is shown in the report). This configuration contains the basic pod device with shells (pod-housing) and a lengthened vertical drive shaft for sufficient propeller submergence. A streamlined body is fitted around the drive shaft for two reasons:

- prevent surface effects around drive shaft;
- prevent drive shaft drag being included in the measurement of unit thrust.

In this test set-up a number of problematic issues can be observed, including:

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

For the first of these, there is a gap between pod-housing and propeller hub which affects the measurement of propeller thrust – the gap size required at model-scale is reported by the Committee to be currently unclear. Measurements are reported from the open literature regarding the effect of the propeller gap width on the propeller and on the pod open water performance; two showing a significant effect and one in contradiction. Two of the three investigations indicate that the gap width on model-scale mainly affects the propeller thrust, but neither the propeller torque nor the total pod thrust. This means that propeller thrust measurements on propellers fitted to pods are giving unreliable results. The reason is attributed to a pressure built up in the gap which affects the propeller thrust measurement. Because this gap force also works on the front end of the pod-housing, it counteracts the gap force on the propeller and thus the total unit force is not affected. Notwithstanding, the gap effect may not be an immediate obstacle for power prediction. However, the propulsion factors, particularly wake fraction obtained from a propeller thrust identity, can be important for propeller design. This will be affected by the gap effect if the gap widths are considerably different between the set values for the pod open water test and self-propulsion test.

The Committee concluded that the performance of a puller-type propeller could only realistically be measured by measuring the torque as a function of advance coefficient J. Further investigations are required to determine how reliable propeller thrust measurements can be realised. The Committee notes that, this matter is of utmost importance for the propeller design.

The Committee report also about the gap between strut top and the lower end-plate of the test set-up – the gap size required at model-scale is also currently unknown. Also, if the strut top section is not horizontally level it is not clear if the propeller shaft should be set up horizontally. The gap between the top of the strut and the end-plate should preferably be kept as small as possible. This is because it is mostly non-existent at full-scale – at least at the vertical shaft location where the unit is fitted into the hull. Nevertheless, a certain gap is required to allow some motion in the pod relative to the endplate.

If the pod strut has an inclined top section in the open water test set-up, it is advisable to make it horizontal by adding a wedge. This will prevent an uneven strut gap that will affect the pod performance by influencing the local flow. This wedge will add some wetted surface area to the pod, but it is expected that its effect on the pod resistance is much smaller than the effects of an inclined strut top section. The effect of this gap on the pod performance is considered to be quite small.

It is suggested that the pod drive open water test be carried out using the same procedure as described for the propeller open water test. The full-scale correction of propeller K_T and K_Q should be done in the same manner as for a propeller alone.

The Committee also reports that, If the streamlined body shape is not similar to the strut shape, unknown 3-dimensional flow effects may occur. To prevent 3D flow effects over the strut affecting the open water performance of the pod, the streamlined body should be made similar to the strut, but mirrored in the strut top section to create a double-body flow, which cancels local vertical flow effects over the strut. This is however, a rather time- and money-consuming method – for every pod to be tested a new streamline body has to be made. Experience has shown that there is a much simpler method which creates a very similar effect: a thin metal plate fitted horizontally below the streamlined body and extending far enough in a forward and a transverse directions to prevent local vertical flow velocities. Care should however be taken not to extend the front end of the plate too close to the propeller of a pulling pod – as this could affect the flow through the propeller disc.

5.3 Pod Drive Self Propulsion Test

The Committee also reports that 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.

Reports from the open literature presented a study on model propulsion test for a twin pod-driven bulk carrier. Results showed that, although the power predictions for both methods were quite close, the propulsion factors of both methods differed considerably.

In pod propulsion tests, the thrust and torque of the propeller are to be measured close to the propeller. The unit-thrust is to be measured by means of an at least 2-component measuring frame at the intersection of the pod-strut with the ship model, on which the motor is fitted. Experience with pod testing has shown that a simple measurement of the unit-thrust by means of a longitudinal force transducer between vertical drive shaft and ship model does not work. This is because the measurement is affected by thrust and torque effects between motor and shaft when the motor is simply fitted to the bottom of the model. A single component unit-thrust transducer can be used in principle, but a minimum 2-component transducer is strongly recommended to be able to check the correct alignment of the pod units in the ship model. Also this allows an easy measurement of pod performance under several pod helm angles, without having to change the direction of the single component transducer [Air leakage and Reynolds scale effects are again of special concern – solutions proposed in the last section are considered appropriate].

For the pod drag, theoretically, the difference between the propeller thrust and unit-thrust should be taken. However, the gap between propeller hub and pod-housing affects the measurement of propeller thrust and thus the determination of housing drag. One way of dealing with this is to carry out pressure measurements in the gap on model scale. However this also necessitates full-scale

measurements for calibration. Alternatively, the pod and propeller open water tests can be conducted as described in the previous sections. Besides leaving all the gap effects with the pod performance, the propeller designer will benefit; being able to design for the propeller thrust requirement. Because the pod-housing drag is too large at model-scale, due to Reynolds scaling difficulties, either the propeller performance or the unit-thrust performance should be set during the pod propulsion tests.
If the applied towing force, contains only the model friction correction force, then the unit-thrust is correctly scaled and can be extrapolated to full-scale. However, in this case the propeller loading is not correct, leading to too high propeller rotation rate, torque and propeller thrust. If the towing force, also contains the housing drag correction, as well as the model resistance correction force, then the propeller performance is correct and can be extrapolated directly to full-scale by the known scaling laws. Now however, the unit-thrust is too low, due to excessive housing drag, and thus the unit-thrust needs to be corrected before extrapolating to full-scale. This means that, for carrying out propulsion tests on ship models with pods, a decision has to be made as to which one of the two methods is to be used.

5.4 Extrapolation Procedure

When open water tests are conducted on a pod unit, again it is recommended to carry out additional runs with a dummy propeller hub on the pod. This is necessary to cancel any propeller hub and gap effects; assuming that the gap effect will not be changed significantly when testing only a dummy hub on the pod model. A further refinement in the dummy hub tests would be to use, as onset flow to the pod unit, the expected mean flow at the propeller plane, i.e. the flow including the propeller induced axial velocities. The induced flow may be estimated using e.g. propeller momentum theory. The measured propeller thrust and torque should be corrected with the results of the dummy hub runs, determining again propeller blade thrust and torque. The total force of the unit exerted on the test set-up, known as unit-thrust and the propeller blade thrust and torque are used to create the well-known open water table and diagram.

5.5 Concluding Remarks on Scaling Issues and Gap - Effects

Pod drive model tests have now been carried out for about two decades. Various pod models, testing methods and extrapolation procedures have been developed for predicting the full-scale performance. Developments in all areas are on-going; partly experimental but, in the last decade, also by means of CFD. Although several obstacles in this process were removed, making methods and procedures slowly converging, there are still several problems to be solved. The two biggest ones are the scaling of pod-housing drag and the propeller-hub gap effect. Further investigations are required to solve these issues. It should be emphasized that full-scale pod performance measurements are strongly required for a better understanding of these scale effects. This should enable the development of methods allowing accurate and reliable full-scale performance predictions.

6. EFFECTS ON PROPELLER WORKING POINT AND OFF-DESIGN CONDITIONS

Finding of the 24th ITTC report that, in contrast to main propulsion systems based on conventional propeller with rudders, pod drives may operate under severe off-design conditions in steering and manoeuvring operations. The hull and pod structure may be subject to extreme loads, which may result in structural failure as well as in motion instability due to large induced initial heel and roll amplitudes. Therefore, the consideration of the off-design conditions is crucial in the design of pod drives and their propellers, as well as in the prediction of propulsive and manoeuvring characteristics of ships driven by these propulsion devices.

6.1 Classification of Off-Design Conditions

The report finds valid argument in the existing literature; discussed in terms of: accelerating; normal steering; extreme steering; stopping.

Acceleration is argued to be substantially the same as for the conventional case. Generally speaking, initially high loads may result in tip-vortex cavitation but will moderate to the design-mode-cavitation-pattern as the ship speed rises. This initial stage is argued to be similar in pattern and risk to that of the bollard-pull condition.

The authors define ‘normal steering’ to be helm angle of $\pm 7\sim 10^{o}$ around the straight-ahead condition. The report suggests that these angles are not expected to pose a danger for the blade strength or cavitation and is most likely smaller than for a conventional arrangement. It is also noted that, if only a lower-fin or flap is present, cavitation risks due to the effect of tip-vortex on a short foil may increase; impact of tip-vortex being considered important (especially with pusher-types).

It is also noted that manoeuvring loads experienced by pods can be shown to be highly acceleration dependant; citing papers presenting experienced spike-loads. It is noted that while these 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 is considered to be acceleration dependent and thus most sensitive to the dynamic course-stability of the ship. Also, it is noted that hull forms suited to the application of pods tend to have poor course-stability. The report suggests that, ensuring the initial design has positive course-stability helps to reduce the magnitude of spike-loads and subsequent induced roll effects.

The most significant component dictating the control force generated by the pod is the strut; acting like a rudder. 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.

For harbour-manoeuvring-conditions, the report defines this as helm angles exceeding $7\sim 10^{o}$, and more typically in the range of $15\sim 30^{o}$. There is considered to be a high probability of cavitation due to both the reduction in the advance-ratio and increase in the incidence angle. Also, this operation mode will exert large manoeuvring induced loads on the entire pod unit due to the acceleration dependency; possibly double that of the steady-state turn condition. The report cites existing literature finding the possibility of roll-angles exciding those acceptable within IMO criteria.

For the crash-stop manoeuvre the report considers this as an emergency situation that involves both ship’s hull and the pod-drive. The main aspects of investigation under this scenario are the forces (in steady and unsteady nature) both on the propeller and on the pod structure, and the behaviour of the ship during the crash-stop manoeuvre. Various modes of crash stop manoeuvres are outlined, including:

- by changing the direction of propeller rotation;
- by turning the pod around;
- by turning the pod to generate steering forces (indirect mode) that oppose forward motion.

For the situation where the crash-stop manoeuvre is achieved by changing the direction of propeller rotation, the authors report the following.

In principle, an electric drive system can provide torque-astern quite comparable with the torque-ahead and hence the propeller reversing time is much shorter than with a mechanical drive. Thus, the propeller starts running full-astern while the ship has still a significant forward speed. This means that, for a pod-drive, the propeller strength is important. One should also take into consideration the unsteady character of the flow around the blades during the crash-stop manoeuvre and accordingly, the unsteady character of the involved hydrodynamic forces. Unsteady cavitation and

flow separation effects associated with the crash-stop manoeuvre would entail high vibrations and the associated noise radiation.
For the situation where the crash-stop manoeuvre is achieved by turning the pod around, the authors report the following.
It is noted that this mode is not applicable for single-screw ships because of the undesirable change in the ship's direction. For twin-screw ships however, it is quite acceptable and usually more effective than changing the propeller rotation. Papers are cited from the existing literature noting that a key problem is the blade loading. It is suggested that the most dangerous helm-angles are about 60~70^o and also when the propeller operates opposite to the ship speed at the final stage of the manoeuvre.
For the situation where the crash-stop manoeuvre is achieved by an indirect mode, the authors report the following.
While again not applicable to single pod ships, for twin pod ships, it is possible to turn the pods to opposite helm angles and thereto use the induced steering force as a braking force (cited from open literature).
Compared to the other methods, the indirect mode demonstrates the shortest stopping time and distance. Cited results show a more sustained braking force but with significantly lower peak loads than when turning the pods around. A further advantage of this 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.
Superior crabbing and dynamic positioning behaviour are advantageous characteristics of pod-driven ships. The authors report that, the problem of how the propeller design could satisfy both the speed and the bollard-pull initially motivated developing Voith-Schneider Propellers (VSP). Nevertheless, after some time, azimuth-thrusters with screw propellers demonstrated that they were quite competitive with VSPs, especially on special-application ships.
Trade-offs involved in the design of screw-propeller thrusters include choices between:

- ducted propellers offer up to 30% advantages in thrust and cavitation-free bollard-pull thrust but are slightly less efficient under design-speed conditions as well as being more sensitive to oblique flows; and
- blades tip unloading improves cavitation characteristics under both design-speed and bollard-pull conditions at high propeller loads but reduces the bollard-pull thrust and is reported to be possibly disadvantageous for lightly loaded CPPs in the DP mode.

Thus, finding the optimum trade-off requires including the analysis results of the propulsion and cavitation tests in the general analysis of ship design.
Cavitation tunnel investigations into bollard-pull conditions pose problems associated with the propeller-induced velocities in a restricted tunnel environment. In this respect the Committee authors suggest best practice with justification.
It is also noted that, special attention should be paid to the crabbing mode when the ship moves with a low speed but the pod drive operating aside in a highly oblique inflow. In this case, ducted propellers are more sensitive to the steering angle and beyond a certain steering angle they suffer flow separation on the duct, which provokes a significant increase in the non-uniformity of the duct velocity field.

6.2 Review of Research on the Off-Design Conditions

The ITTC authors cite examples of published data relating to experimental programs; covering cavitation tunnel tests with a tandem pod (propeller at both ends as well as puller- and pusher-type pods. Tested were conducted at zero and ±15^o drift or steering angles. Comparing the hydrodynamic characteristics of the puller-type and twin-screw thrusters, the authors concluded that the drift angle had a pronounced effect upon the axial hydrodynamic force on the twin-screw pod and a similar though smaller effect upon the puller-type. Propeller rotation direction was found to have some effect on both lateral and transverse forces. Generally, hydrodynamic characteristics are found to be asymmetric with respect to the drift angle.

Other cited papers concluded that the presence of the strut noticeably distorted the free vortex system. The effect of the pod on the geometry of the free vortex system of the fore propeller was small. Also, open-water tests of puller- and pusher-type pods in a rotating-arm basin are reported. The literature describes tests with a complete pod mounted on a 6-component strain-gauge dynamometer. The published detailed plots are very useful for practical applications.

Also cited from the open literature are results of captive tests on a double. The results are used to validate numerical predictions. Time-domain simulations are then used to demonstrate that a significant increase in the pod loads should be experienced when performing dynamic manoeuvres.

Published experimental results on forces and moments on a pod obtained information on the propeller thrust and torque as well as on the three force and moment components within a vast range of advance ratios from wind-milling to locking. In addition the reported results open a new avenue in experimental investigation; including dynamic tests with rotating pods. The report suggests that, in such tests, one should carefully consider the similarity parameters like the ratio between the propeller revolutions and steering rates. By this method, the obtained results indicate that the pseudo-steady approach is acceptable for predicting forces and moments.

The last decade has seen various CFD tools, including Boundary Element Methods (BEM or panel methods), RANS or hybrid potential-flow/RANS methods, applied to performance predictions for pod drives under straight-course and, to a lesser extent, manoeuvring conditions, open publications can offer only very few examples of CFD computations for pod drives under off-design conditions. Examples in the open literature concluded that design-speed steering capabilities of pod drives should not be much better than conventional rudders but at lower speeds there are definitely advantages.

There are no publications on crash-ahead and crash-back manoeuvres dedicated exclusively to pod drives, and the available papers deal with conventional open propellers only. One cited paper applied a RANS code and the ANSYS FEM software for estimating flow characteristics and forces on Siemens-Schottel twin-propeller pods within steering angles 0~30^{o}. The results were compared with experimental data and demonstrated that the accuracy was acceptable for estimating force and moment components.

Considering the propeller under off-design conditions one paper reported an investigation on propellers under extreme off-design conditions such as bollard-pull and crash-back scenarios using PIV and LDV experimental technologies combined with a computational procedure. The approach made it possible to register the behaviour of the ring-vortex. Based on experimental wake data, the authors estimated averaged and extreme loads associated with the crash-back mode, and the obtained peak blade load was 200~250% above mean values. This finding correlates well with numerous publications on pod propeller design that considered the crash stop as the crucial point in the pod-drive strength analysis because of the very quick and powerful crash-stopping typical of electric pod-driven systems.

6.3 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.

7. EXPLORE 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.
(Kurimo, 1998) 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^o 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.
(Lepeix, 2001) 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.
(Hamalainen and Van Heerd, 2001) reported 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^o of maximum heel angle restriction was enforced for safety reasons.
(Toxopeus and Loeff, 2002) investigate 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 conven-

tionally 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^{o}/s slewing rate; compared to a value of 2.32^{o}/s for the rudder. As already stated in Section 8.2 within the framework of roll stability, 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 (OPTIPOD, 2000) project 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; reported in (Woodward et al., 2002b). 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. In a review of the manoeuvring performance (Woodward et al., 2003) 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.

(Woodward et al., 2002) present 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 10/10 zig-zag overshoot angles.

(Kurimo and Bystom, 2003) 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.

(Pustoshny and Kaprantsev, 2001) 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 5~7^{o} helm angle for course keeping. They also observed that the risk of cavitation during steady turn was far higher than the effect of (10~15^{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.

(Boushkovsky et al., 2003b) 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, (Woodward et al., 2005) 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.

8. EXPLORE THE 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.

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