Intuitive operation and pilot training when using marine azimuthing control devices

AZIPILOT

Report Title:

Deliverable 2.3:

Review of ability to simulate azimuthing device interactions

PUBLISHABLE EXECUTIVE SUMMARY

The aim of this task was to establish the ability to simulate the interaction between azimuthing control devices of existing simulators. The capability and validity of the modelling used for the most common situations has been reviewed, namely:

- Exploring the effects of hull-form on azimuthing control device performance;
- Establishing non-linear effect in azimuthing control device performance;
- Reviewing operational models and effects on interactions.

This study concluded that most existing simulator modules for podded propulsive drives do take into account propeller thrust, transverse propeller forces, and lift and drag forces on the pod body. They also adequately model the interaction effects between different pod units, and shallow water effects on podded vessels.

The second objective of this task focussed on the results of a survey of pod manufacturers and operators, to establish the ability of simulators to replicate interactions between multiple azimuthing control devices, and between those devices and the ship‟s hull.

The results of the survey shows that interaction between two or more podded propulsors is important and it may affect the manoeuvring characteristics of a vessel in certain modes of control. When using large manned models for training this effect is automatically taken into account. However the effect of scaling down propellers on the interaction is not known and there are no indications how it may influence manoeuvrability.

Data is available on the interaction between a *Pod* and the form of the ship‟s hull, in particular on the effect of skegs and fins. The installation of skegs and fins improves dynamic stability, however at the same time making the turning ability characteristics slightly worse. How this effect is taken into account in mathematical models is uncertain, but some data from experiments with ship model tested without skegs or fins. Or models tested with skegs or fins of different sizes installed are available and may be used.

Data on wake and form coefficients for ships with podded propulsors currently cannot be found in publications, but such data are certainly available as a result of model tests performed in towing tanks when testing ship models for shipyards. Evaluating these coefficients in the case of manned models is not a simple task however.

1. INTRODUCTION

The present Report covers predominantly interactions effects between ship hull and various components of the (gondola, propeller and strut); Hydrodynamic aspects and simulation technique and simulation results in regard to the hydrodynamic performance and manoeuvring of the ship equipped with the *azipods* have been discussed in our previous report. The first of three sections, section 2 considers Pod modelling is considered to be a critical element for realistic modelling, and pod is treated as a separate entity with a suitable allowance for the pod-hull-interaction.

Section 3 considers the modelling and programming of Azimuthing Pods in PC Rembrandt, this modelling is split into three sections,3.1 Estimating the influence of other pod or prop wakes on the inflow velocity and angle of attack, 3.2 Estimating the pod inflow velocities and angle of attack and 3.3 Estimating the pod forces on the ship. The model employed has been designed to be generic in both a mathematical and a programming sense, to allow its application to a wide range of ship and stern configurations.

Sections 4 aims were to survey existing simulator capabilities with respect to the ability to simulate the interaction between azimuthing control devices. The objective is to review the capability and validity of the modelling used for the most common situations including, 4.1 Survey data regarding interactions between multiple azimuthing control devices and 4.2 Survey interactions between azimuthing control devices and the ship hull form.

Simulation of the manoeuvring and handling capabilities of ships fitted with podded propulsion is important for the industry. It is essential to use detailed modelling when calculating the propeller design characteristics and coefficients.

2. OUTLINE OF THE TECHNIQUES TO MODEL MULTIPLE PODS – HULL INTERACTION.

The pod modelling in turn is considered to be a critical element for realistic modelling, and pod is treated as a separate entity with a suitable allowance for the pod-hull-interaction. The hydrodynamic approach adopted by most simulators around the world (and by BMT and by Transas techniques described below) is based on the modular approach assuming that the total hydrodynamic forces can be estimated as an integral sum of the forces due to the pod, gondola and strut and their interaction forces with the hull and between each of them as well. Specifics at each methodology are different but in most of the simulation models the pod is assumed to be a streamline body with the strut submerged in a flow shadowed by a hull. The pod housing drag including the effect of propeller action can be assumed to be:

$$R_{pod} = R_{body} + R_{strut} + R_{int} + R_{lift}$$

Where the above terms are components of the pod resistance (or lift if we estimate lateral forces) associated with pod body (nacelle), strut, and pod body – strut interference and lift effect due to swirling flow action of the propeller. There are several reliable techniques describing each of the above components (see additional references in survey of the publications on the subject) and their accuracy typically within 10% error range or less. This accuracy is considered to be quite sufficient for any simulation manoeuvres for ships with *Azipod* Steering and Propulsion Units.

Principal features of the Hydrodynamic Interaction between *Azipods* and Ship Hull

Propeller transverse force in oblique flow

Figure 1 shows schematically the top view of a ship stern fitted with two pods. The ship is moving forward, so that the propellers are subjected to an inflow acting at an angle to the longitudinal axis of the pods (oblique inflow). In this case there appears a force acting at 90° to the longitudinal axis of the pod (i.e. a transverse propeller force), as shown in the figure. This transverse force is due to the change of direction of the flow particles as they flow through the propeller disc.

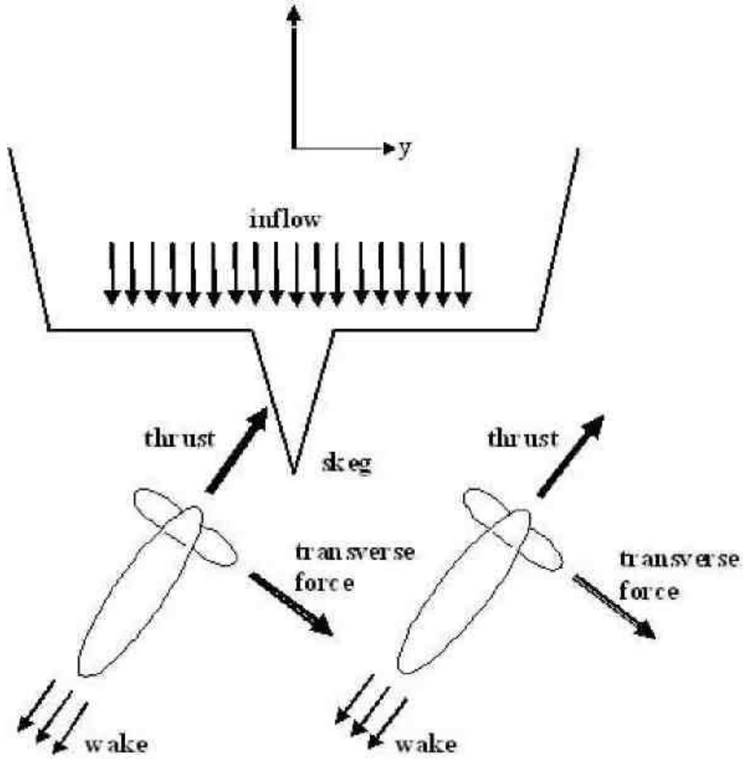


Fig. 1 transverse propeller force (top view)

Pod / pod interaction

A ship fitted with more than one pod has to be modelled taking accurately into account pod / pod interactions: when, for instance, the wake of one (“upstream”) pod impinges on a nearby (“downstream”) pod, the “downstream” pod experiences a loss of thrust due to the higher inflow velocity imparted by the upstream pod. Furthermore, this modified flow pattern (i.e. speed magnitude and angle of attack) affects both lift and drag of the pod body etc.
Figure 2 shows schematically the top view of a ship stern fitted with two pods. The ship is at rest and the pod is turned on 90 degrees angle

A positive thrust (i.e. to starboard), its wake (jet flow) impinges on the port pod behind it, which experiences a drag force counteracting the starboard pod thrust.

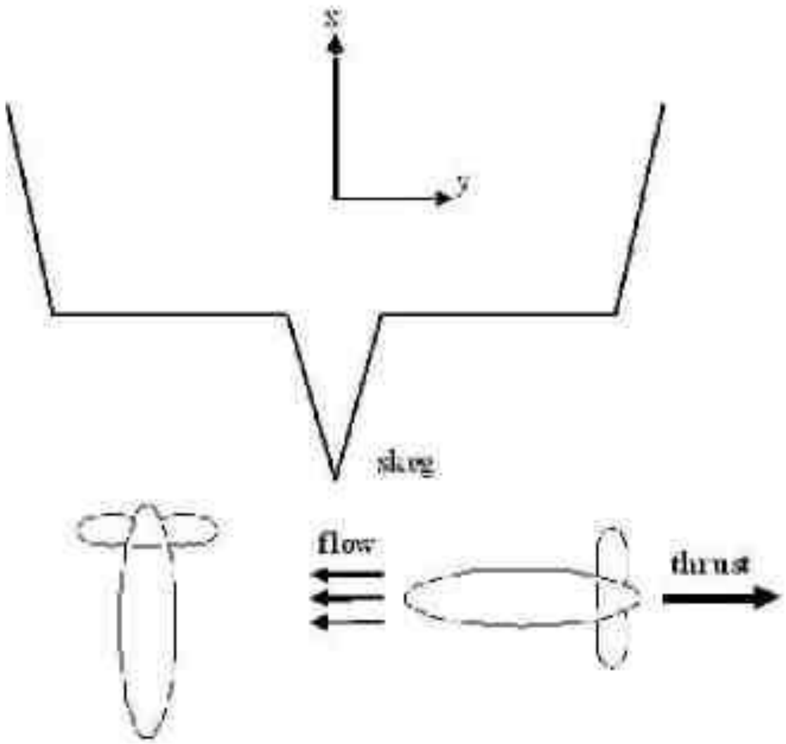


Fig.2 example of pod / pod interaction (top view)

Pod / hull interaction

A major effect to be taken into consideration is the interaction between the pod propeller jet flow and the ship hull geometry. Figure 3 shows schematically once again the top view of a ship stern fitted with two pod units. Moreover, the ship has a centreline skeg: one of the main advantages of the podded propulsion over the conventional one is its improved propeller efficiency due to the better inflow into the propellers. This inflow has to be directly aligned with the contours of the stern and the pod units positioned to suit these. Ship designers achieve this favourable alignment of flow by choosing a stern shape which is much more "open" than that of a ship with conventional propulsion. But since this "open" stern type may lead to an undesired loss of course stability, a large central skeg (i.e. a fixed fin) in this case is often fitted [4]. The ship is initially at rest. While the port pod remains inactive, the starboard pod is turned to an azimuth angle equal 135 degrees.

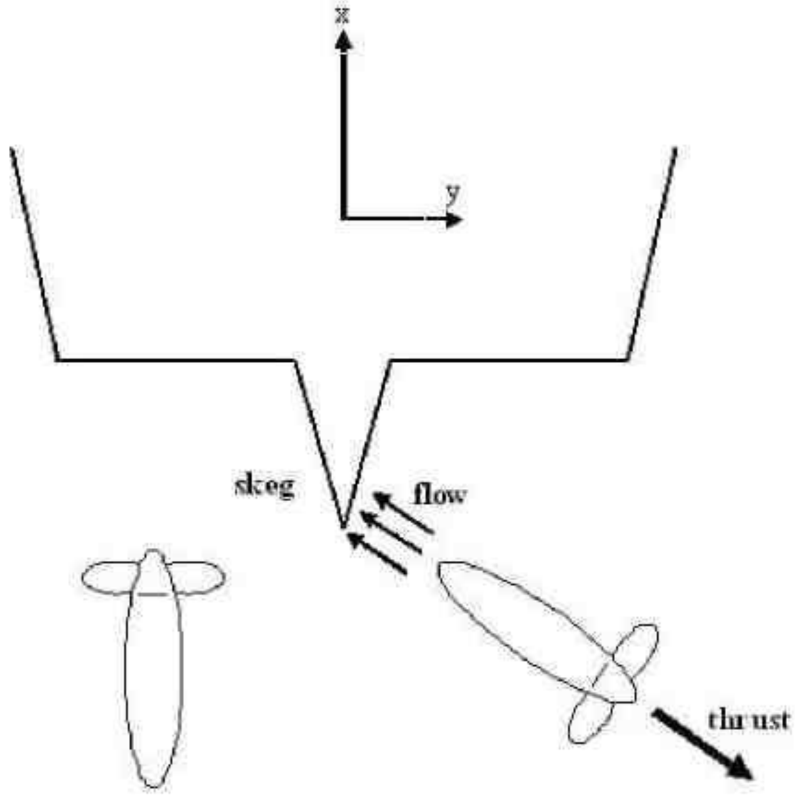


Fig.3: Example of pod / hull interaction

In every simulation time step therefore the local surge and sway speeds at each pod are obtained by adding the "exit wake speed" of all "upstream" pods to the local forward and lateral velocities due to the ship motion. The "exit wake speed" of the pod is modelled in a simplified manner as a jet flow, the direction of which is opposite to the thrust generated by the pod propeller. Moreover, we take into account the decrease of the flow intensity behind the propeller disk along the pod axis, since the greater the distance from the pod along the axis, the less intense the jet flow gets.

A propeller generates thrust by accelerating the water particles flowing through its disk. In the situation depicted above though these accelerated particles impinge on the nearby skeg generating, in turn, a force opposing the propeller thrust: the thrust is therefore apparently "reduced". In some cases this interaction effect can even lead to a zero resultant, so that the ship does not turn at all (in the sea trials performed by RDE with the pollution control ship "Arkona" this phenomenon was accompanied by violent structural ship vibrations).This effect is carefully accounted for in the mathematical model.

Finally, the greater the thrust, the farther behind the propeller disk the effects of the propeller jet will be noticed. A relatively low thrust level in the example above, on the other hand, may lead to a lower "thrust reduction" than that with the pod working at maximum RPM.

Water depth effect

The hydrodynamic properties of both, the ship hull and the propulsion/steering units change depending on water depth. The rudder efficiency e.g. may greatly increase in shallow waters. In most of simulators shallow water effects affecting the ship manoeuvrability are taken into account:

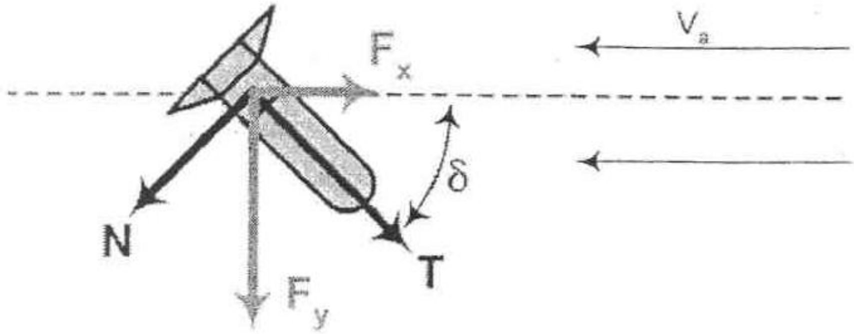
- Hydrodynamic hull forces; and
- Pod forces depend on the current water depth.

This is achieved by making key coefficients associated with the pod model dependent on the water depth.

Model validation and Comparison Propeller Simulation / Model tests

To validate the mathematical model the open-water propeller diagram of an azimuth propeller measured in a model test series is typically calculated. The advantage of this comparison is that the azimuth propeller forces can be analyzed free from interaction effects with the ship hull: the propeller forces in the open-water diagram are determined in a homogeneous inflow.

In the open-water propeller diagram, see figure 4, the measured "surge" (i.e. longitudinal) and "sway" (i.e. transverse) forces are depicted dependent on the propeller deflection angle (0° through 360°): the resultant Force is decomposed into a longitudinal X - and a transverse Y - component (i.e. FX and FY).



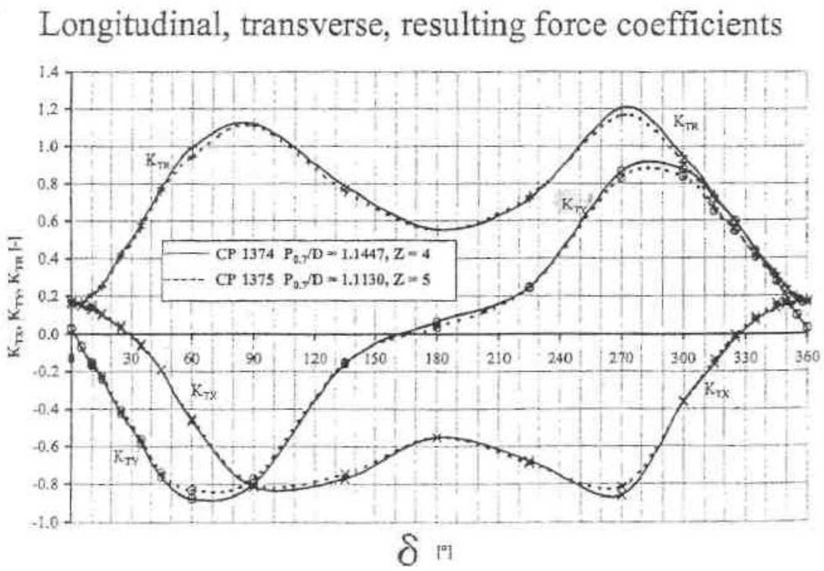


Fig.4 open-water propeller diagram

The comparison between simulation and measurement for deflection angles between 0° and 180° is presented in figure 5 showing a very good agreement.

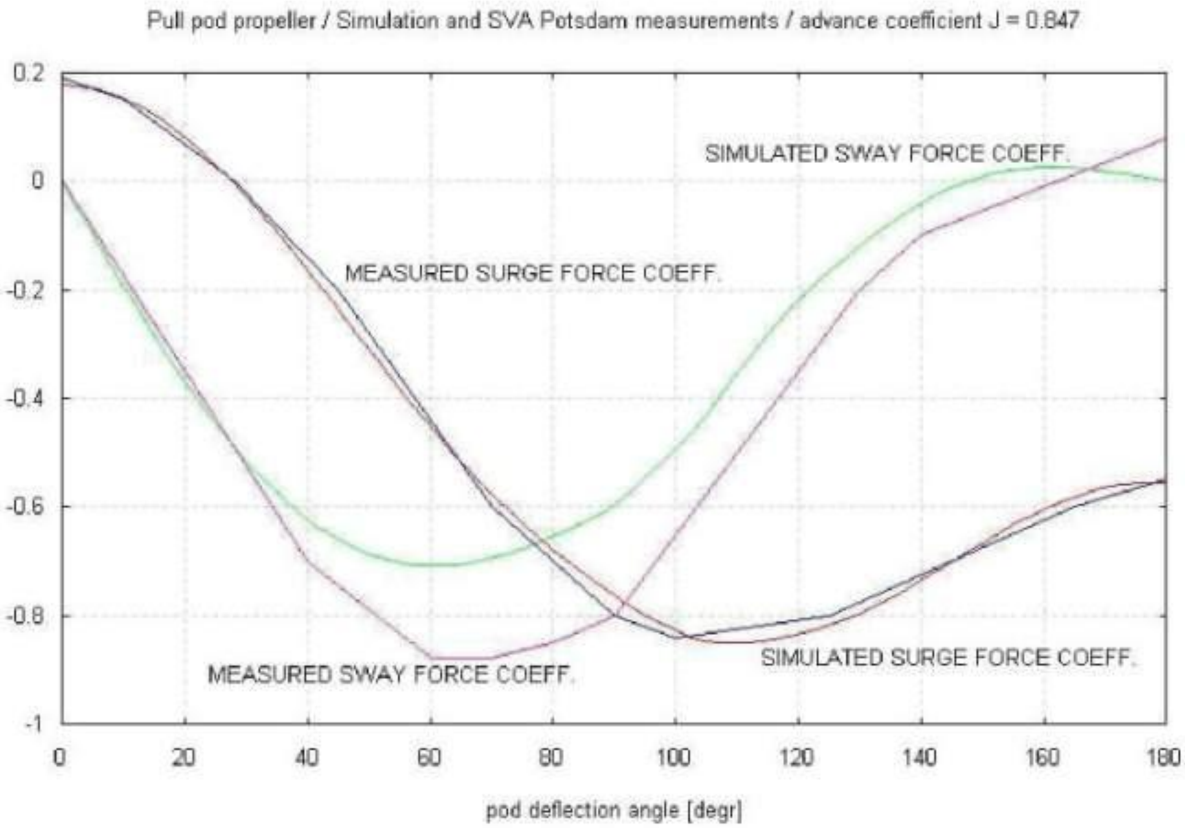


Fig.5 open-water propeller diagram: comparison simulation /measurement

Comparison Ship Simulation / Sea trial measurements: The German pollution control ship "Arkona" and the Hapag-Lloyd passenger vessel "Europa"

Arkona

Comprehensive two-day trials with the German pollution control ship "Arkona" were conducted by RDE especially for gathering comprehensive data on podded ship manoeuvring. They took place in November 2005 in the Baltic Sea.

Table 1: Arkona (Design particulars)

Length o.a.	69.2 m
Beam	15.0 m
Draught	3.9 m
Propulsion	Diesel electric 2 pod units, type SEP2 (i.e. Schottel Electric Propulsion)
Power	3700 kW
Maximum speed	13 kn

The podded unit SEP2 is of twin propeller type. Figure 6 shows both a lateral and the top view on the ship's stern.

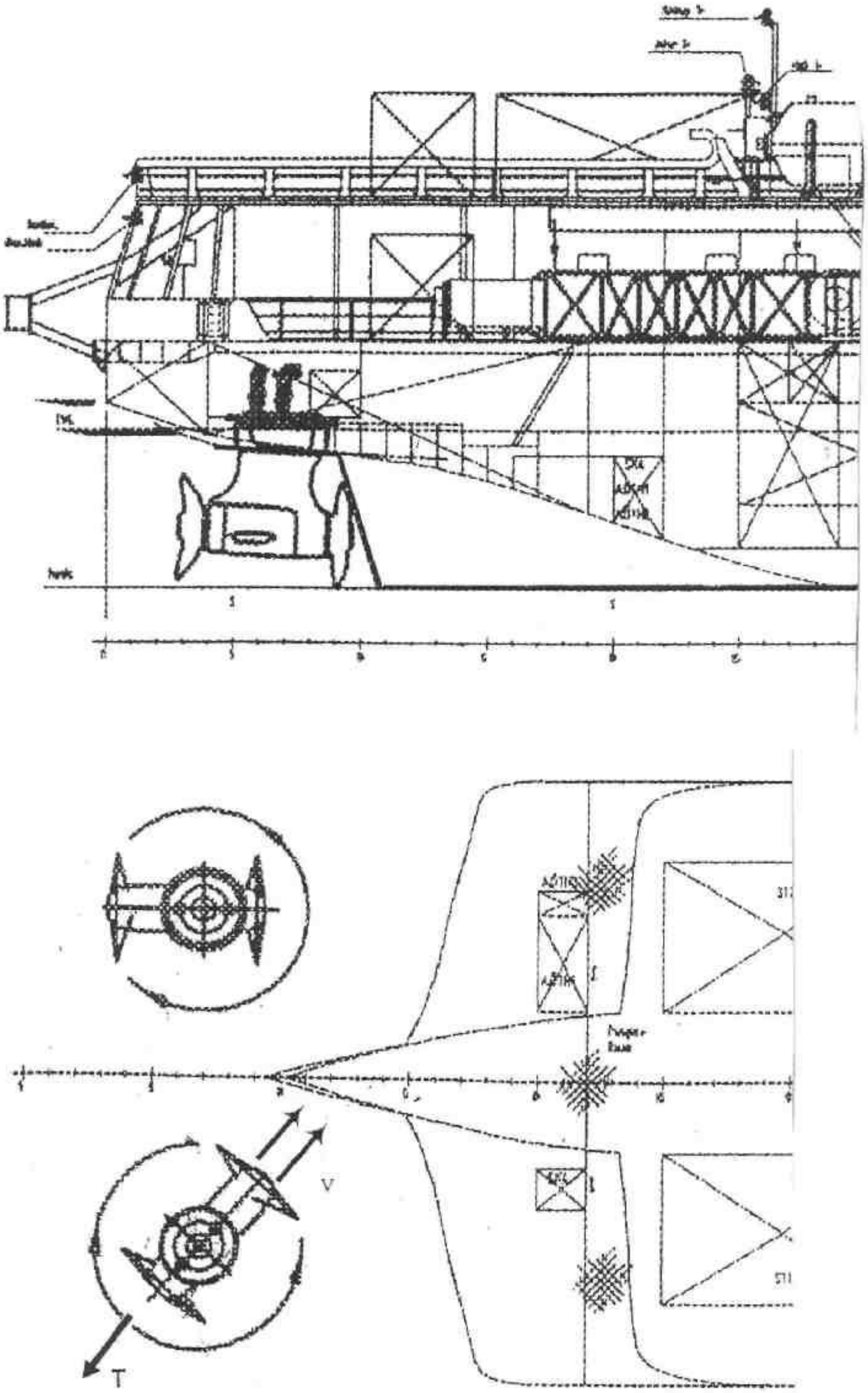


Fig.6 stern of the pollution control ship "Arkona"

The “Arkona” was a very interesting choice as a test ship because of her large centreline skeg: due to the close proximity of the pod units to this skeg a substantial pod / hull interaction was predicted. This was expected to happen when e.g. the port pod unit delivers a thrust T (see figure 6) at an angle somewhere between 90° and 180°: the propeller jet flow V impinges then on the skeg generating there a force that counteracts this thrust. Various tests were performed during the “Arkona” trials including:

- Turning circles;
- Zig-zag manoeuvres;
- Stopping trials;
- Manoeuvres at zero speed with one pod only;
- Manoeuvres at zero speed with both pods.

These tests were carried out both in deep and in shallow waters. A number of comparisons between the simulation results and measurements for the “Arkona” are presented in the following diagrams. Note that positive angles (propeller deflection, rate of turn (ROT) etc.) are defined in the clockwise direction.

Figure 7 shows ROT results for a manoeuvre, in which the ship turns “on the spot”: after the “Arkona” had been stopped, her starboard pod was commanded to 90° (i.e. thrust to starboard) while the port pod remained inactive at 0°. Then, the starboard pod was commanded to maximum thrust causing the ship to turn to port (negative ROT). The propeller jet was directed to port impinging on the inactive port pod and inducing thus – among other effects – an additional drag to starboard reducing the final ROT.

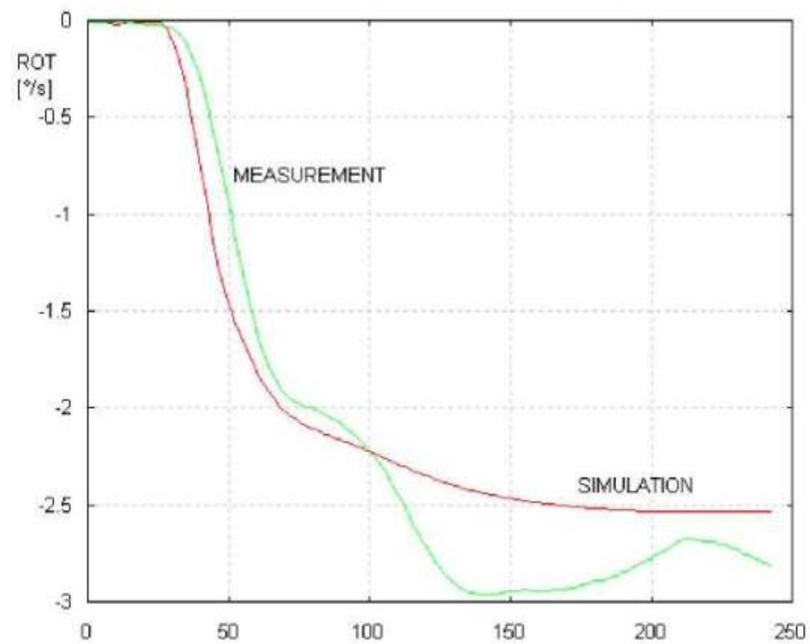


Fig.7 comparison simulated manoeuvre/measurement

Next - as a contrast to the example above - a similar manoeuvre with the stopped ship is shown (see figure 8). The only difference between this new manoeuvre and the previous one is that the starboard pod is now commanded to –90° (i.e. thrust to port). In this case, since the propeller jet is directed away from the ship, the magnitude of the (positive) ROT is substantially higher.

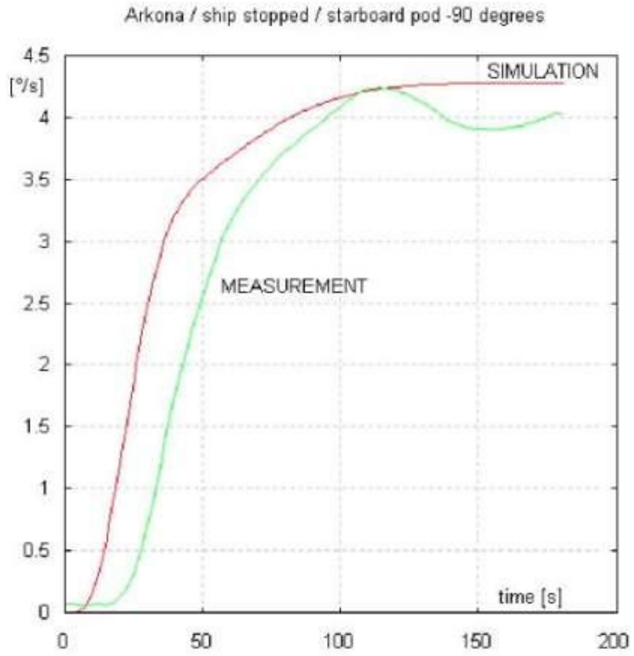


Fig.8 comparison simulated manoeuvre/measurement

A further example with only one active pod is shown in figure 9. The starboard pod delivers maximum thrust at an angle of 45°, so that the propeller jet impinges neither on the hull nor on the port pod.

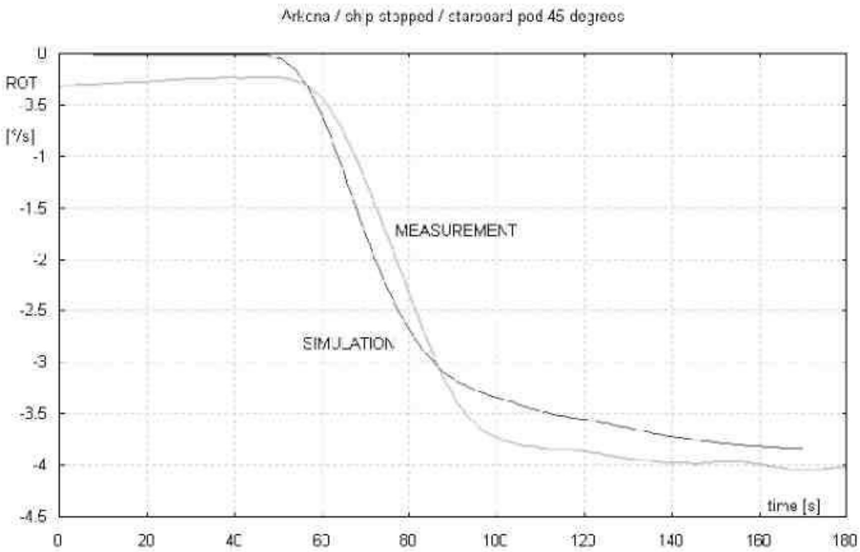


Fig.9 comparison simulated manoeuvre/measurement

Finally, figure 10 shows a standard stopping manoeuvre: after the ship had achieved maximum speed both pod propellers were quickly commanded from full-ahead to zero RPM causing the ship to come slowly to a stop (the smooth curve is the simulated speed through water, the other line is the actual values).

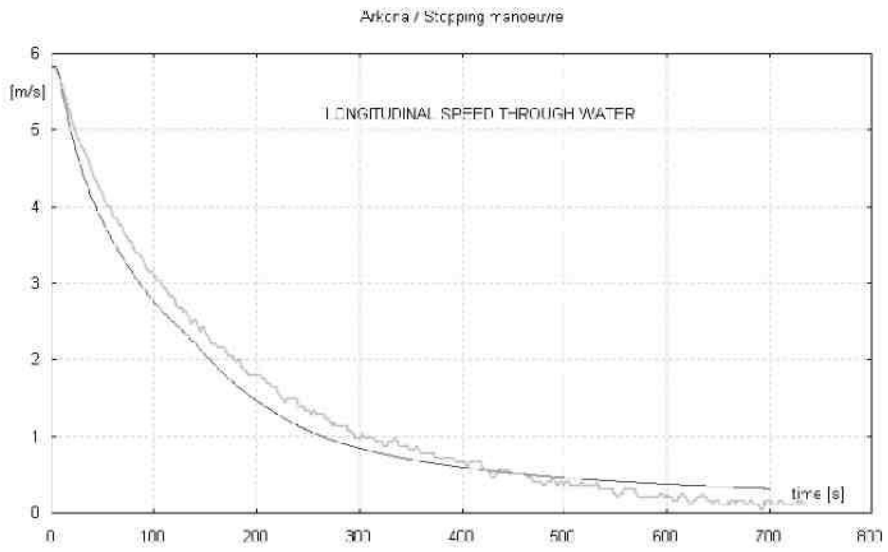


Fig.10 comparison simulated manoeuvre/measurement: stopping manoeuvre

MS Europa
A further application of the new RDE pod model is the simulation of the Hapag-Lloyd passenger ship "MS Europa]:

Table 2: MS Europa (Design particulars)

Length o.a.	198.6 m
Beam	24.0 m
Draught	6.0 m
Lateral wind area	4217 m²
Propulsion	Diesel-electric 2 ABB pod units
Power	21600 kW
Maximum speed	approx. 21 knots

The "MS Europa" thus greatly differs from the "Arkona" in particulars such as size, type of superstructure and maximum speed. Comprehensive manoeuvring data are available from recorded shipyard trials. Unfortunately, these trials were conducted in wind speeds of over 20 knots). The following tables show a comparison between simulation and measurement (N.B. t90 is the time required for a 90° heading change, t180 for a 180° change).

	Manoeuvre to Port		Manoeuvre to Starboard	
	Simulated	Actual	Simulated	Actual
Starting Speed [kts]	21.40		11.40	
EOT [%]	100		60	
Rudder Angle [deg]	35.0		-35.0	
Advance [m]	404.0	379.6	333.0	364.4
Transfer [m]	165.0	159.1	167.0	164.3
Tactical Diameter [m]	375.0	392.1	382.5	398.7
Turning Circle Diameter [m]	320.0	313.7	323.5	320.3
Steady Speed at steady turn [kts]	6.40	6.59	3.90	4.38
t90 [sec]	56	54	91	96
t180 [sec]	117	120	182	203
t270 [sec]		192		314
t360 [sec]	260	264	397	425

Table 3:Turning circle tests with both pods at an angle 35°:

	Manoeuvre to Port		Manoeuvre to Starboard	
	Simulated	Actual	Simulated	Actual
Starting Speed [kts]	10.50		10.50	
EOT [%]	80		80	
Rudder Angle [deg]	35.0		-35.0	
Advance [m]	399.0	430.6	402.0	434.0
Transfer [m]	205.0	210.5	201.0	210.7
Tactical Diameter [m]	497.0	480.3	466.0	492.2
Turning Circle Diameter [m]	496.0	403.2	506.0	419.7
Steady Speed at steady turn [kts]	4.80	5.04	4.80	5.06
t90 [sec]	115	118	117	121
t180 [sec]	217	234	244	242
t270 [sec]		356		368
t360 [sec]	471	478	529	494

Table 4: Turning circle tests with starboard pod only at an angle 35°:

	Manoeuvre to Port		Manoeuvre to Starboard	
	Simulated	Actual	Simulated	Actual
Starting Speed [kts]	10.50		10.50	
EOT [%]	80		80	
Rudder Angle [deg]	60.0		-60.0	
Advance [m]	309	377.5	322	376.1
Transfer [m]	133	143.6	136	139.3
Tactical Diameter [m]	287	293.0	253	276.4
Turning Circle Diameter [m]		53.3		33.5
Steady Speed at steady turn [kts]	1	0.46	2	0.29
t90 [sec]	99	112	102	114
t180 [sec]	191	206	198	207
t270 [sec]		294		296
t360 [sec]	402	377	423	382

Table 5: Turning circle tests with starboard pod only at an angle 60°:

Note: due to the wind speed (over 20 knots) no direct comparison is possible when the speed of the ship during the manoeuvre is much reduced (e.g. at the end of the manoeuvre in the table above)..

	Simulated	*Actual*
1st Overshoot [deg]	*6.5*	*6.8*
2nd Overshoot [deg]	*8.1*	*9.0*
3rd Overshoot [deg]	*7.9*	*8.3*
t(1st Overshoot) [sec]	*36*	*29*
t(2nd Overshoot) [sec]	*94*	*76*
t(3rd Overshoot) [sec]	*146*	*135*

Table 6: Zig-zag tests 10° / 10° with both pods

	Simulated	*Actual*
1st Overshoot [deg]	*3.9*	*3.9*
2nd Overshoot [deg]	*5.1*	*6.0*
3rd Overshoot [deg]	*4.0*	*5.1*
t(1st Overshoot) [sec]	*71*	*69*
t(2nd Overshoot) [sec]	*180*	*178*
t(3rd Overshoot) [sec]	*298*	*295*

Table 7: Zig-zag tests 10° / 10° with starboard pod only

Conclusion

Most of the existing simulator modules for podded propulsive drives take into account:

- Propeller thrust;
- Transverse propeller force;
- Lift and drag forces of the pod body;
- Interaction effects between different pod units;
- Interaction effects between pod and shallow water effects.

3. DESCRIPTION OF THE MODELLING OF AZIMUTHING PODS IN PC REMBRANDT

The following is a general description of the methods applied to the modelling and programming of Azimuthing Pods in PC Rembrandt – a mathematical model. As far as practically possible, the model has been designed to be generic in both a mathematical and a programming sense, to allow its application to a wide range of ship and stern configurations. As part of this, the methods have been programmed to allow them to be applied to propellers, rudders and azimuthing thrusters, as well as tunnel thrusters where applicable. The modelling may be split roughly into three sections:

- Estimating the influence of other pod or prop wakes on the inflow velocity and angle of attack
- Estimating the pod inflow velocities and angle of attack
- Estimating the pod forces on the ship.

These are described below.

Interaction between Pods and other Manoeuvring devices

The model proposed for use in this section was developed by Ian Dand for the interaction of azimuthing ducted propellers. The observed loss in thrust of a propeller in another propeller‟s wake is modelled by estimating the accelerated wake velocity emerging from the upstream propeller, and applying this to the inflow velocity of the downstream propeller. The main advantage of this velocity approach is that it can also be applied to the inflow velocity of any manoeuvring device (rudders, propellers, pods...) downstream of a propeller. The wake velocity emerging from the thruster is calculated according to Barnaby:

$$V_e = \sqrt{\frac{4|T|}{\pi D^2 \rho . slip}}$$

We then apply the following limits on the slip:

$slip = 0$: For $Pn = 0$

$slip = 0$: For $\left|\frac{U_P}{Pn}\right| > 1$

$slip = 1$: For $\frac{U_P}{Pn} < 0$

$slip = 1 - \left|\frac{U_P}{Pn}\right|$: Otherwise

However, as slip tends towards zero, V_e will increase towards infinity, and hence the model gives largely erroneous results. In a manoeuvring simulation, this is a frequently recurring scenario, and hence it was decided that this model is not appropriate for use in Rembrandt.

Instead, either one of the two existing methods for estimating propeller wake velocity will be used. The first method is based on pitch and slip and is shown below:

$V_e = Pn(1 - 0.418.slip)$ For $X_T \geq 0.00001$ and $v_{inflow} \geq 0$

$V_e = v_{inflow} + 0.5Pn$ For $X_T \geq 0.00001$ and $v_{inflow} < 0$

$V_e = v_{inflow} + 0.1Pn$ For $X_T < 0.00001$

Where slip is given by:

$$slip = \frac{Pn - v_{inflow}}{Pn} \qquad \text{For } |Pn| > 0.001$$

$$slip = 0 \qquad \text{For } |Pn| \leq 0.001$$

The second is an application of momentum theory:

$$\left.\begin{array}{ll} V_e = v_{inflow} - \sqrt{\dfrac{8k|T|}{\pi\rho D^2}} & :\text{for } v_{inflow} > 0 \\ V_e = v_{inflow} + \sqrt{\dfrac{8k|T|}{\pi\rho D^2}} & :\text{for } v_{inflow} < 0 \end{array}\right\} :\text{for } \; v_{inflow}{}^2 + \frac{8k|T|}{\pi\rho D^2} < 0$$

$$\left.\begin{array}{ll} V_e = \sqrt{v_{inflow}{}^2 + \dfrac{8k|T|}{\pi\rho D^2}} & :\text{for } v_{inflow}T > 0 \\ V_e = \sqrt{v_{inflow}{}^2 - \dfrac{8k|T|}{\pi\rho D^2}} & :\text{for } v_{inflow}T < 0 \end{array}\right\} :\text{otherwise}$$

Where: k is a commonly accepted empirical correction factor applied to the thrust.

The test $v_{inflow}{}^2 + \frac{8k|T|}{\pi\rho D^2} < 0$ avoids taking the square root of a negative number, and evaluates to true when the propeller thrust reverses the flow direction. Hence, this approach may be applied to any values of inflow velocity and propeller thrust, lending itself well to use in manouevring situations. Further, the form used above allows it to be applied either upstream or downstream of a propeller, by applying either the upstream or downstream multiplication factor to the velocity (the downstream factor obviously being much larger). As the relative separation of the components in a podded ship (i.e. pod to pod, or pod to fin) is quite large, the upstream effect of a propeller is ignored by setting the upstream multiplication factor to zero in each component. The existing method, however, had to be extended to determine whether the component in the propeller‟s wake was actually upstream or downstream. Whereas this was very simple to determine with conventional propellers, the following had to be applied for pods.

First, a line connecting the centre of the propeller to the centre of the component within the wake is produced, and its angle to the ship‟s centreline, θ_1, calculated. Next, it is known that the propeller‟s wake will run at an angle, θ_2, equal to the azimuth angle of the propeller.

In applying a similar form of the momentum equation to azimuthing ducted thrusters, *Brandner and Renilson (1998)* found the best experimental-theoretical correlation with $k = 0.43$. As their tests were performed at a thruster separation/diameter ratio of 1.3, and no wake velocity attenuation was applied, applying our wake velocity attenuation (see below) we should use $k = 0.456$ to achieve similar results. Previous comparisons of the two wake velocity estimation methods above in Rembrandt have required a k of the order of 0.5 to achieve reasonable correlation, thus giving extra confidence to the 0.456 factor above.

As V_e is the absolute wake velocity (as opposed to the increase in velocity), to fit in with the existing Rembrandt model, we must now calculate the increase in velocity of the jet over the propeller inflow:

$$V_J = V_e - V_{inflow}$$

Where V_{inflow} is the advance velocity of the propeller (parallel to the prop axis), as described in section 3.2 below.

The wake is assumed to be a straight cylinder extending downstream from the propeller. The criterion for checking the „downstream" direction is the sign of Pn (positive indicating „ahead" thrust, and negative indicating „reverse" thrust). Increase in the wake cylinder"s diameter is accounted for by a multiplication factor in the input file. This value should typically be of the order of 1 – 1.2. Attenuation of the wake velocity with distance is taken by interpolation of the following points:

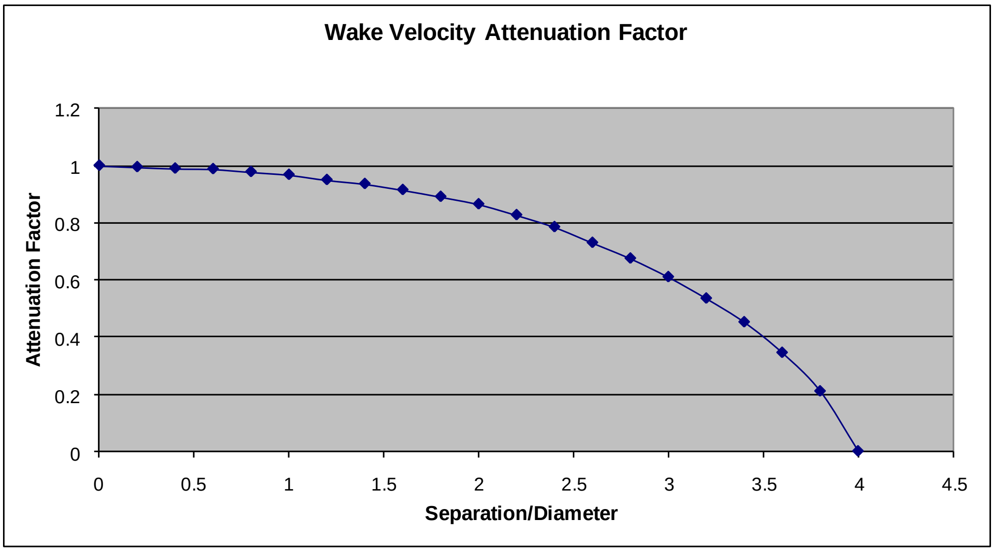


Fig.11 Wake Velocity Attenuation Factor

Hence: $V_{J2} = V_J$ * attenuation factor

This curve forms part of the input file, and hence may be altered for different components if required. Experimental data points up to an S/D of approx. 3.5 were used to create this curve, and hence we should be able to use it with confidence within this range. However, it should be noted that the graphs of thruster interaction (of unknown origin) provided by RCI indicated a significant influence on thrust up to an S/D of 13 and above.

Next, the influence of this wake on a downstream component must be taken into consideration. In this case the component in consideration is a pod or thruster; however, the same method will also be applied to calculate the inflow velocity of a rudder, skeg or propeller.

The first step is to check whether the component in question is influenced by the wake of another, and subsequently, by how much. As the original model tests were performed by rotating an „upstream" thruster and measuring the effect on the downstream thruster, our model follows a similar approach.

The next step is to calculate the upstream thruster azimuth angle (θ_1) such that its wake just starts to impinge on the downstream thruster. Next, the angle where the whole of the downstream thruster is within the wake of the upstream thruster is calculated. (θ_2). This is illustrated in the diagram below:

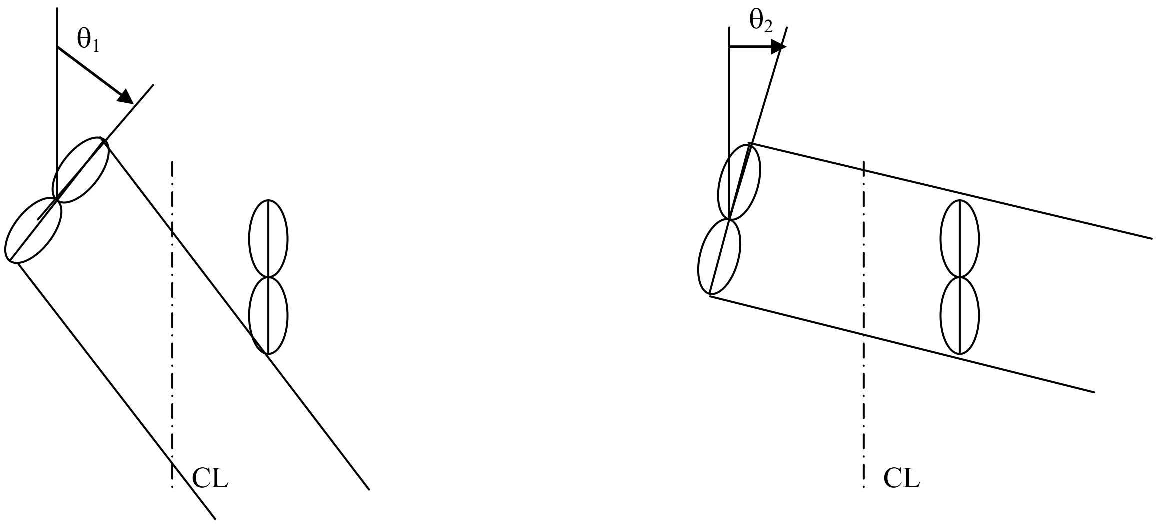


Fig.12

If the actual azimuth angle is between θ_1 and θ_2, the following equation is evaluated:

$$f = \frac{\theta - \theta_1}{\theta_2 - \theta_1}$$

Where f is effectively the proportion of the downstream thruster within the wake. The „effective" wake velocity that the downstream thruster sees is then calculated thus:

$$V_{Jeff} = V_{J2} \sin(f \frac{\pi}{2})$$

The same is applied to the azimuth of the upstream thruster in the opposite direction; so that we obtain the other defining angles θ_3 and θ_4 (equivalent to θ_1 and θ_2 respectively, but on the opposite side). Plotting this effective V_J against upstream thruster azimuth angle, θ gives a sine curve based relationship which has been chosen as it best approximates the model test results.

If the relative dimensions of the upstream and downstream components are such that there are no angles θ_2 and θ_3, (i.e. the wake never wholly covers the downstream component) then the flat spot between these two values on the above graph is removed, and the curve becomes simply a sin curve between θ_1 and θ_4. This case will form the majority of scenarios.

As indicated by the graph, the actual velocity seen by the downstream thruster will be the vector sum of V_{Jeff} and the *'free-stream'* velocity. This is described further in section 3.2 below.

In the event that the wakes from two separate pods or props impinge on a downstream component simultaneously, V_{Jeff} is taken as the vector sum of the two V_{Jeff}"s. This approximation is assumed to be sufficient for the initial model, and may be altered later if necessary, or if more data becomes available. From the drawings of the Voyager of the Seas provided in Appendix B, it can be seen that with the present velocity attenuation curve, neither skeg will ever be under the influence of two wakes. It is only the fixipod that may be influenced by two wakes simultaneously, and in this case, as the direction of the two incident wakes will be at or close to 180 degrees opposed, the vector sum approximation should be sufficient.

The drawings in Appendix B also illustrate the influence of the aft of the keel (i.e. the *Fixipod*) on the wake interaction of the two azipods. The „blocking" effect of the keel on the *Azipod's* wake is modelled by introducing a flow barrier. This barrier is defined in an input file as a line (or series of lines) with a blockage factor, such that, on the downstream side of the barrier:

$$V_J = V_J * blockagefactor$$

The intersect of a pod"s wake and the barrier is taken at the wake"s centreline. The resultant V_{Jeff} is then calculated in the same manner as described above.

1.1 Calculation of Pod Inflow Velocities

The ship velocities must first be resolved into velocities at the pod

The surge and sway velocities (u_{10}, v_{10}) of the ship at the pod (x_1, y_1) are equal to:

$$u_{10} = (u - ry_1)(1 - w_T(1 + 0.2\zeta) \quad : \text{for } (u - ry_1) > 0$$
$$u_{10} = (u - ry_1)(1 - 0.2w_T(1 + 0.2\zeta) \quad : \text{for } (u - ry_1) \le 0$$
$$v_{10} = v + rx_1$$

Where ζ is the usual depth correction factor and w_T may be different for each pod or propeller. Notably, w_T is assumed to stay constant with varying drift angle β, and is only applied to the surge component of the ship velocity; hence we are assuming that there are no wake effects in the sway direction. This is in keeping with the existing Rembrandt model. Next we must add the wake velocity of any upstream pods if applicable:

$$u_1 = u_{10} + v_{jeff} \cos\theta_i$$
$$v_1 = v_{10} + v_{jeff} \sin\theta_i$$

Where θ_i = upstream pod (or prop) azimuth angle (positive to port).

The present Rembrandt model takes account of hull flow straightening effects when calculating rudder inflow velocity, but not when calculating propeller inflow velocity. Therefore, to keep the model similar, and to aid in backward compatibility, flow straightening will not be applied to pods. As ships with podded propulsion will have more open sterns than conventionally propelled ships, this assumption should be reasonable. Should this assumption prove to cause problems in modelling podded ships, Appendix A contains the method for including flow straightening effects on the pods. Next, we must resolve the local velocities (u_1, v_1) into pod axes, such that:

$$v_{inflow} = u_1 \cos\theta + v_1 \sin\theta$$
$$v_{sideways} = u_1 \cos(\theta + \frac{\pi}{2}) + v_1 \sin(\theta + \frac{\pi}{2})$$

Where v_{inflow} is the velocity resolved along the propeller axis, and $v_{sideways}$ is the velocity component perpendicular to the prop axis. Theta is the pod azimuth angle. We must now calculate the resultant inflow speed and direction to the pod. This is done by the existing rudder code, and is calculated thus:

$$v_{resultant} = \sqrt{u_1^{\,2} + v_1^{\,2}}$$
$$\alpha_1 = a\tan(\frac{v_1}{u_1})$$
$$\alpha = \theta + \alpha_1\left[k_{flow} + (1 - k_{flow})(1 - \cos(\alpha_1)\right] : \text{for } |\alpha_1| < 90^0$$
$$\alpha = \theta + \alpha_1 \quad : \text{for } |\alpha_1| \ge 90^0$$

Where θ = pod azimuth angle (positive to port) and α is the pod angle of attack. k_{flow} = flow straightening factor (usually set to 0.55 for conventionally propelled ships in Rembrandt). As the flow straightening cannot be removed from the existing rudder code, we introduce the k_{inflow} term above, which shall be defined separately for each component. By setting k_{flow} = 1 for pods, we effectively ignore flow straightening effects. Further, this also allows this effect to be tweaked for conventionally propelled ships.

Calculation of Pod Forces

The forces of the pod are calculated as per the existing rudder code. Given the non-dimensional lift and drag coefficients of the pod (for 0, 10, 20, 30....180 degrees) this code calculates the rudder (pod) forces in the ship axes. As the data computed for the pod coefficients is in pod axes, we must first convert these to lift and drag coefficients (inflow axes) to fit with the existing code. This process is done off-line, and is simply calculated thus:

$$C_L = Y'\cos\alpha + X'\sin\alpha$$

$$C_D = Y'\cos(\alpha + \frac{\pi}{2}) + X'\sin(\alpha + \frac{\pi}{2})$$

Where *X'* and *Y'* are the non-dimensionalised forces in pod axes. Then, the pod forces in ship axes are calculated as follows:

$$L = \frac{1}{2} pC_L S(v_{resultant})^2$$

$$D = \frac{1}{2} \rho C_D S(v_{resultant})^2$$

$$F_{Xrud} = D\cos(\alpha - \theta) + L\sin(\alpha - \theta)$$

$$F_{Yrud} = D\cos((\alpha - \theta) + \frac{\pi}{2}) + L\sin((\alpha - \theta) + \frac{\pi}{2})$$

The thrust force and torque of the pod"s propeller are calculated in the usual manner:

$$T = (1-t)K_T \rho n^2 D^4$$

$$Q = K_Q \rho n^2 D^5$$

Where *t* is the thrust deduction factor.

As the pressure field around the stern will change with pod azimuth angle, by definition, the thrust deduction factor should change with azimuth angle. Hence, the single thrust deduction factor in Rembrandt has been replaced with an array of values for pod azimuth angle, θ = 0, 10, 20, 30.....360. Used in podded ships, the flow straightening effects of the hull will now be definable for each component (including props).

Lateral forces of the propeller are, however, treated differently to conventional propellers. As the calculated total pod *Y* forces that proved comparable to the Kamewa test results did not include prop bias forces, these shall be omitted. Practically, this is achieved in Rembrandt by simply setting the U_o reference velocity for screw bias to zero in the *.prp* file, thus avoiding alterations to the source code. The momentum drag force created by flow through the prop disk at right angles to the propeller axis is calculated in the existing manner:

$$Rm_0 = \rho n^2 D^4 \left[\frac{\pi}{2} J_{sideways} \sqrt{\frac{|K_{to}|}{\pi}} \right]$$

Where: K_{To} is the K_T at $J=0$, and $J_{sideways} = \frac{v_{sideways}}{nD}$

At present, Rembrandt then modifies this force before applying it as a sway force and yaw moment on the ship. These modifications are to account for flow variations around the hull, and as they don‟t include azimuth angle as a parameter, they are not included in the calculation of pod forces. Hence, the total surge, sway and yaw forces on the ship from a pod are equal to:

$$F_{xpod} = F_{xrud} + T\cos(-\theta) + Rm_0 \sin(-\theta)$$
$$F_{ypod} = F_{yrud} - T\sin(-\theta) + Rm_0 \cos(-\theta)$$

Typical semi-empirical procedure adopted by Transas and by other simulators around the world

Here is a brief outline of the adopted procedures to estimate the longitudinal and lateral pod hydrodynamic force components. Pod in the “behind” condition acts in a time-space variable flow of local surge, sway and yaw velocities together with the propeller slipstream velocities. So that the effective longitudinal and transverse velocities at the pod become simply:

$$Up = [ua + r\,yp + uj] \qquad (1)$$

$$Vp = [\gamma_v \times v + \gamma_r \times (r \times xp)]$$

Here $u_a = u\,(1 - w_p)$ is the advance velocity, u_j is the propeller slipstream velocity at pod location, y_p and x_p are x, y are rudder coordinates respectively (x_p is typically around -½ L), and γ_v and γ_r represent the resultant influence of both, ship geometry and flow- straightening effects on the pod angle due to the ship drift angle (or lateral velocity) and yaw angular velocity, respectively (they are frequently called *“flow rectification”* factors). This implies an effective angle of attack, α_p, will be estimated as a function:

$$Ap = -atan2\left(\frac{uux}{uuy}\right) \qquad (2)$$

Where:

$$uux = U_p\ cos\delta - V_p\ sin\delta$$
$$uuy = U_p\ sin\delta + V_p\ cos\delta$$

The effective velocity over the pod is:

$$U_{eff} = \sqrt[2]{(uux)^2 + (uuy)^2}$$

The lift (Lift) and drag (Drag) components developed by the rudder in “behind conditions” are a function of the square of the speed inflow to the rudder

The hydrodynamic forces in X and Y directions induced by the pod, X_{pod} and Y_{pod}, respectively, become simply:

$$X_{pod} = Lift\sin\alpha_R - Drag\cos\alpha_R$$

$$Y_{pod} = Lift\ \cos\alpha_R + Drag\ \sin\alpha_R \qquad (3)$$

Below are some specifics on estimation of the hydrodynamic forces in above formulas. In Transas model, the hydrodynamic forces acting on pod, streamline body and strut along with their mutual interactions are estimated primarily from the extensive model test results with the large models of the fine forms hulls of the commercial and military ships. The test results have been non-dimensionalised and input into the simulation program in the form of three-dimensional data base, as function the Froude number (up to the value of 0.55) and effective flow in the vicinity of the pod.

4. DATA SURVEYING

The aim of these sections of the task is to survey existing simulator capabilities with respect to the ability to simulate the interaction between azimuthing control devices. The objective is to review the capability and validity of the modelling used for the most common situations including:

- Survey data regarding interactions between multiple azimuthing control devices**;**
- Survey interactions between azimuthing control devices and the ship hull form.

In simulation of manoeuvring and handling capabilities of ships fitted with podded propulsion it is essential to use propeller module that includes a detailed modelling of podded propulsor in four quadrants and that takes the inflow direction to the propeller and velocities distribution at the propeller into account when calculating the propeller thrust and torque. In multiple POD propulsion system both inflow direction and velocities distribution to the POD are affected by the other POD or PODs.

A model where the thrust is just represented as a rotating force with varying magnitude according to the handles setting is simply not sufficiently accurate. (Sorensen et al 2000). The authors are of the opinion that in order to achieve sufficient accuracy the ship own mathematical model must be used and that means that accurate data of thrust and torque of the propeller must be used in the mathematical model that take into account the interaction effects between two or more PODs and between PODs and the hull.

Survey data regarding interactions between multiple azimuthing control devices

Basic control modes with twin azipod configuration

Three basic control modes for ships fitted with two azimuthing propulsors (PODs) are as follows (The Naval Architect, 1996):

1. Cruise mode, using both PODs deflected to the same angle, in a similar way as it is usually done with two rudders in twin-screw ships fitted with conventional propellers
2. SOFT manoeuvring mode, when one POD (left or right, depending on the direction of turn) is used to perform manoeuvres
3. STRONG manoeuvring mode, where both PODs are used to perform manoeuvres

The three control modes are illustrated below:

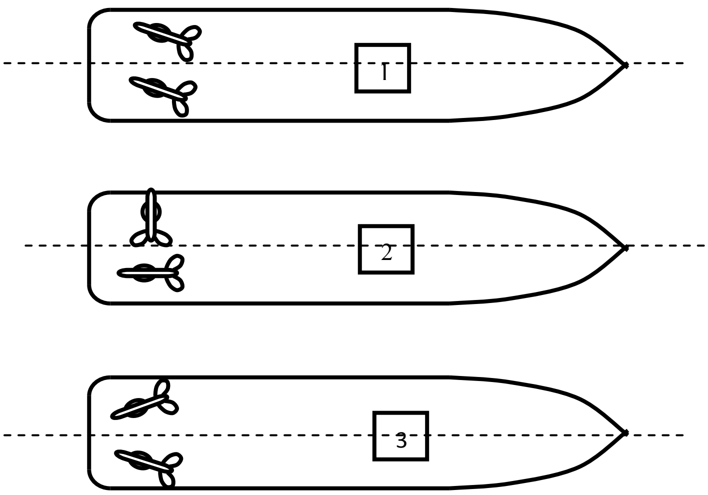


Fig.13

Strong interaction may be expected when one POD is working in the propeller slipstream of the other one and this is affecting considerably thrust and torque. When working in the mode 1 it may happen when PODs are deflected to angles between about 60 to 120 degrees both sides (Fig.14). Similarly when PODs are working in mode 2 and 3 one may expect strong interactions during manoeuvres if one POD get into propeller slipstream of the other. This is the case with PODs fitted with pulling propellers as well as fitted with pushing propellers. The interaction effect may be different if at the stern of the ship one long skeg or fin is fitted that may distort propeller slipstream.

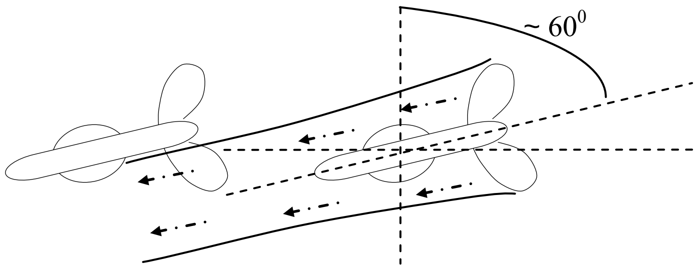


Fig.14

The search for data related to the interaction effect between multiple PODs returned few results. There are actually no publications providing such data, few publications describing these effects and no publications investigating these effects from the theoretical point of view. Some indication how one POD is affecting the other one may be seen from tests performed by, Grygorowicz (2005)

Tests were performed using large manned model of a gas carrier fitted with two podded propulsors having tractor type arrangement (pulling propellers). Measurements were taken when POD"s were working in the *'cruise mode'*. The forces and moments were measured on the POD axis as shown schematically in Fig 16. Measurements were taken on one POD during circulation manoeuvre with different angles of rudder to both sides. As circulation was both ways, the POD on which measurements were taken once was inside of the circle the other time was outside. It is expected that with large angles of rudder the outside POD is strongly affecting the inside one (Fig.15).

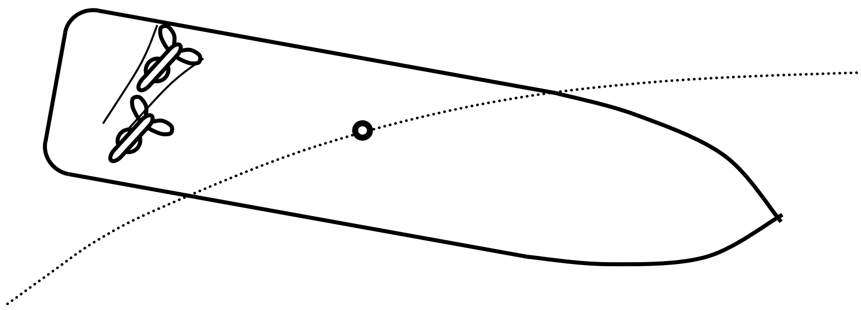


Fig.15

Comparison of results of measurements of forces F_x and F_y, for rudder angle around 70^0 reveal this effect (Figs. 17, 18, 19 and 20). It can be seen that forces are larger when POD"s are deflected to starboard in comparing when they are to port. However in order to obtain formulae or method of calculation systematic measurements should be undertaken including positioning pods in other modes of control.

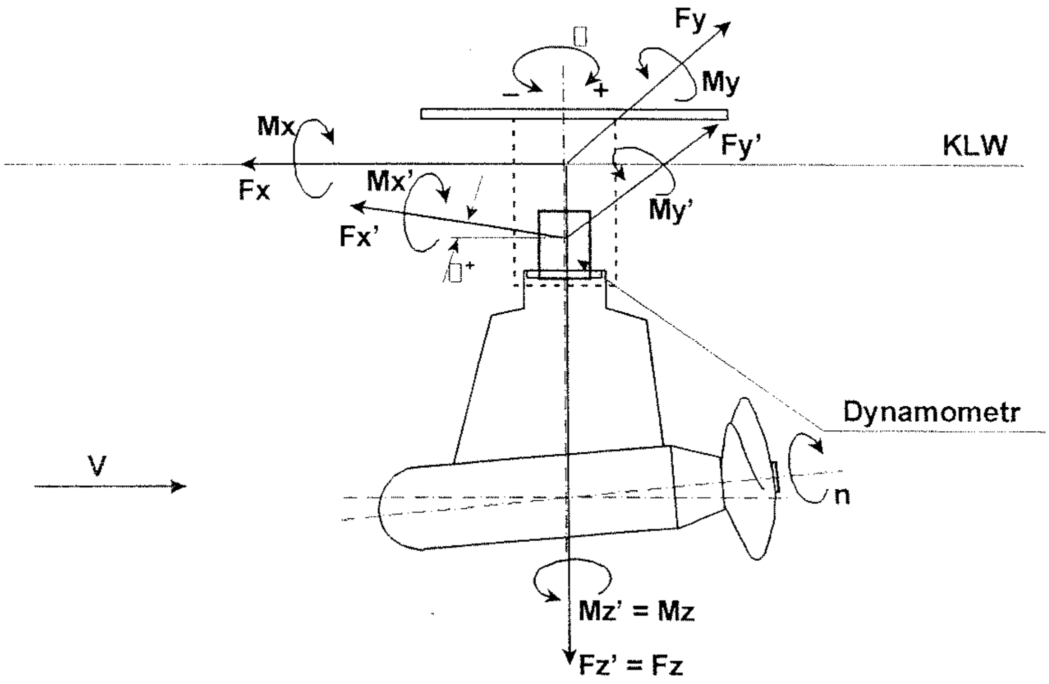


Fig.16

Currently (June 2010), there are no theoretical investigations of these effects published. However there are papers published on the effect of propeller race, of one propeller on the work of the other propeller. Results of this work could be used for an estimation of the interaction effect between two PODs working in the position when they may affect each other. These tools are based on calculation of velocity field behind propeller assuming that the other propeller is working in the velocity field of the propeller in front. Reference is made to the series of papers by Koronowicz et al (2009). The Koronowicz et al, developed a computer code using lifting line and lifting surface models and used computation fluid mechanics methods. The method was successfully used for calculations of tandem and contra-rotating propellers. However it could be used also for calculation of podded propulsor characteristics working totally or partially in the slipstream of the other propeller. However this method was not yet applied to investigating this effect and it is not certain whether it will be applied in foreseeable future.

A simplified method of taking into account this effect was used in the simulation program ANS 5000 that is referred to below (de Mello Peters 2008). It appears, however, that at present in order to obtain reliable data on the interaction effect between PODs and on the effect of one POD on the other when two or more PODs are used the best way is to perform model experiments in a towing tank where measurements of forces and moments of PODs were taken.

This data could be then used in a mathematical model for a ship handling simulation programme, for the particular ship. There is also general lack of data for estimation of POD forces in oblique flow, which exist when the ship is performing a turning manoeuvre. Figs. 17 to 20 provide some indication of this effect. It can be observed that the POD forces vary, not only because of the reduction of speed when performing a turning manoeuvre, but also because the POD" are working in oblique flow. They are also different for the POD working on the leeward side or on the opposite side.

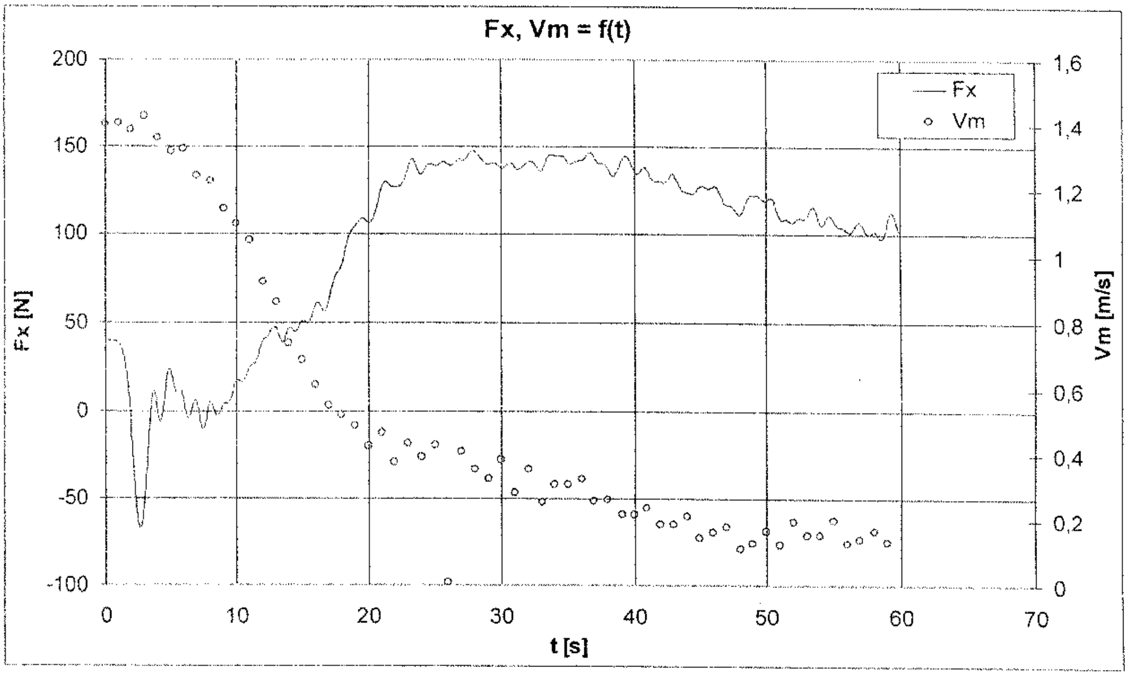


Fig.17

δ= 70.05^0 PORT, speed V=13.4 kn   n= 498 1/min

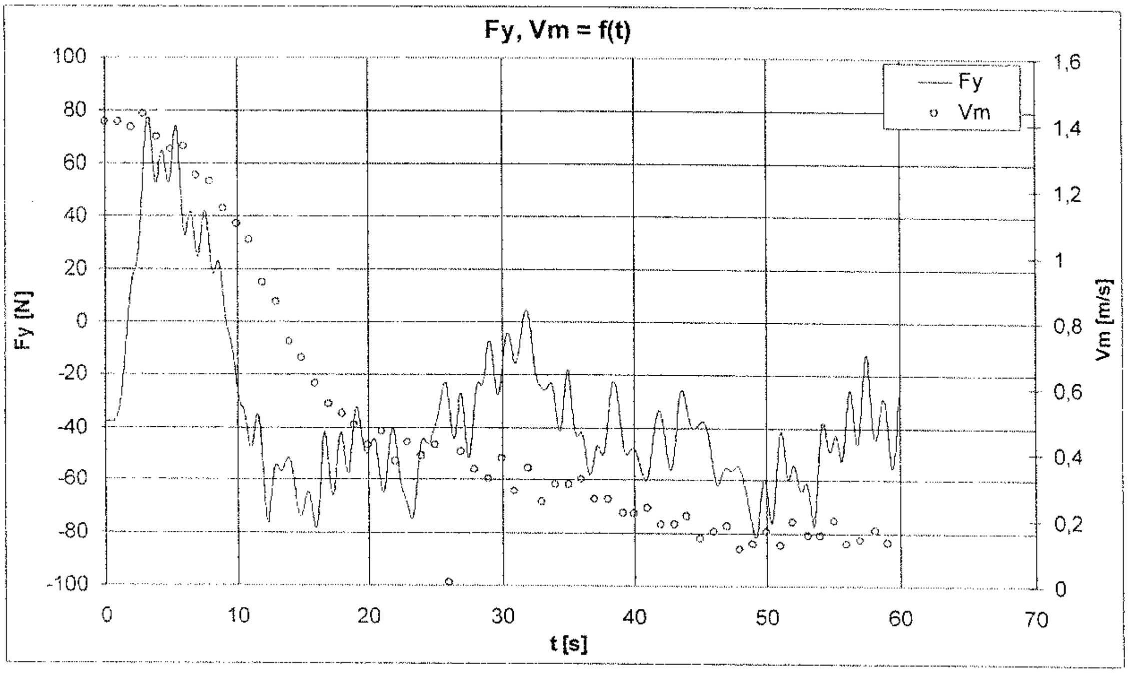


Fig.18

δ= - 68.65^0 STARBOARD, speed V=14.4 kn   n=500 1/min

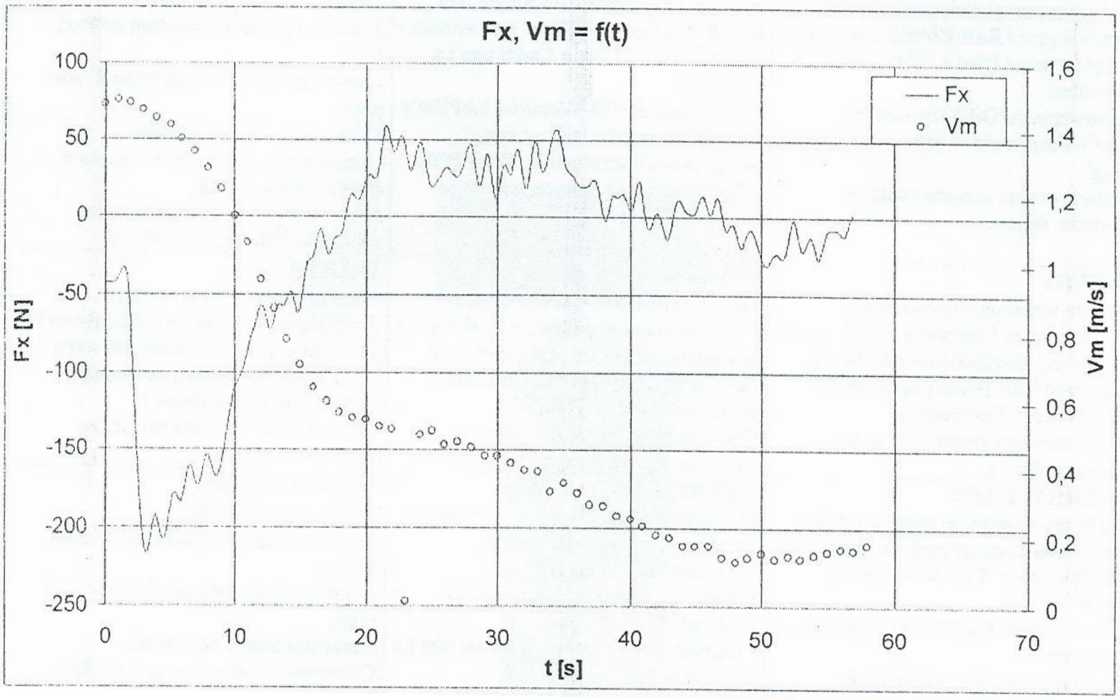


Fig.19

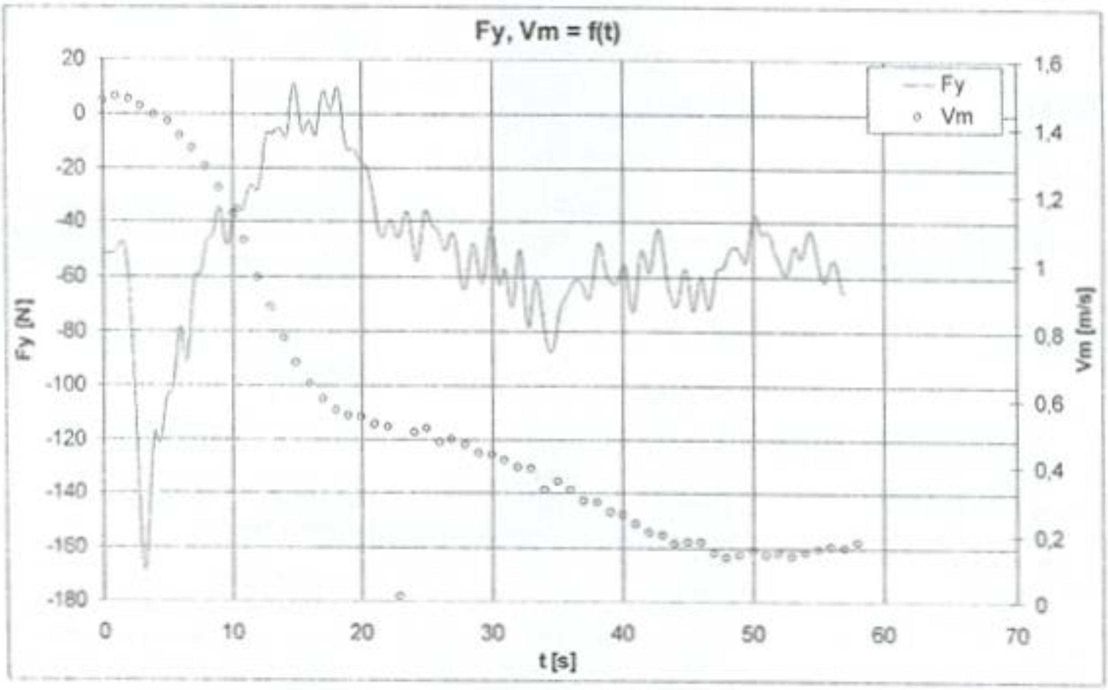


Fig.20

The angle of water inflow to the POD is shown in Fig. 21. The data were obtained from the tests of ROPAX model fitted with PODs on PMM facility (Kanar et al 2002). The Fig 21 shows that this angle depends on drift angle and on the position of the POD whether it is on leeward side or on the opposite side.

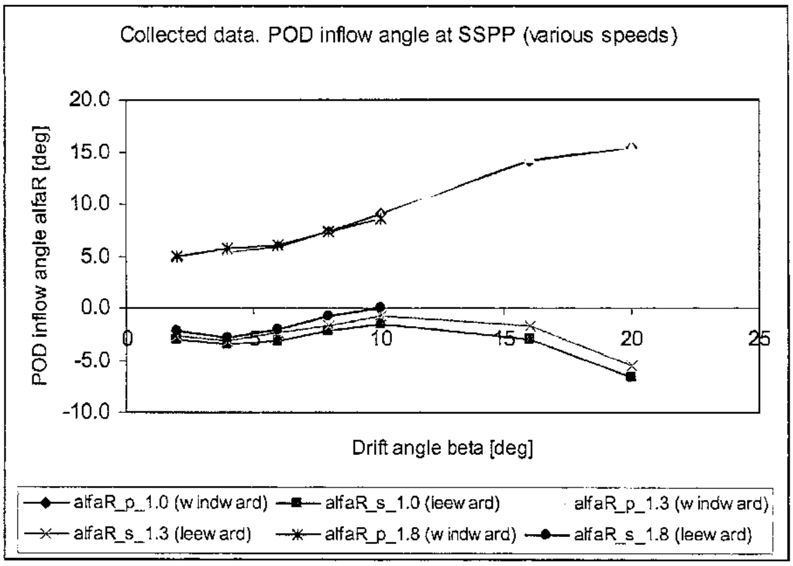


Fig.21. The angle of water inflow to POD. (Kanar et al 2002)

POD–POD interaction was considered by; de Mello Petey (2008), the author claims that this effect is taken into account in the simulation module ANS 5000 developed in Germany. In the position of the starboard POD being turned to 90^0 whether the port one is at rest (Fig 22), the propeller race of the starboard POD is against the port POD creating the force reducing the starboard thrust.

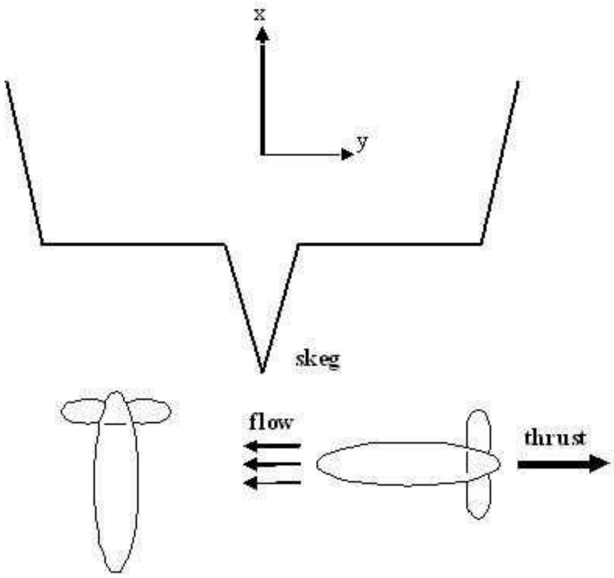


Fig.22.

Fig.23 is taken from de Mello Petey, (2008) this reference shows comparison of simulated manoeuvre and measurements taken onboard of the ship ARKONA. Ship was stopped, the port POD was at rest at zero angle, whether the starboard POD was commanded to 90^0 (thrust to starboard) causing the ship turn to port. The race of the starboard POD was against the port POD causing additional drag to starboard and reducing the turning moment.

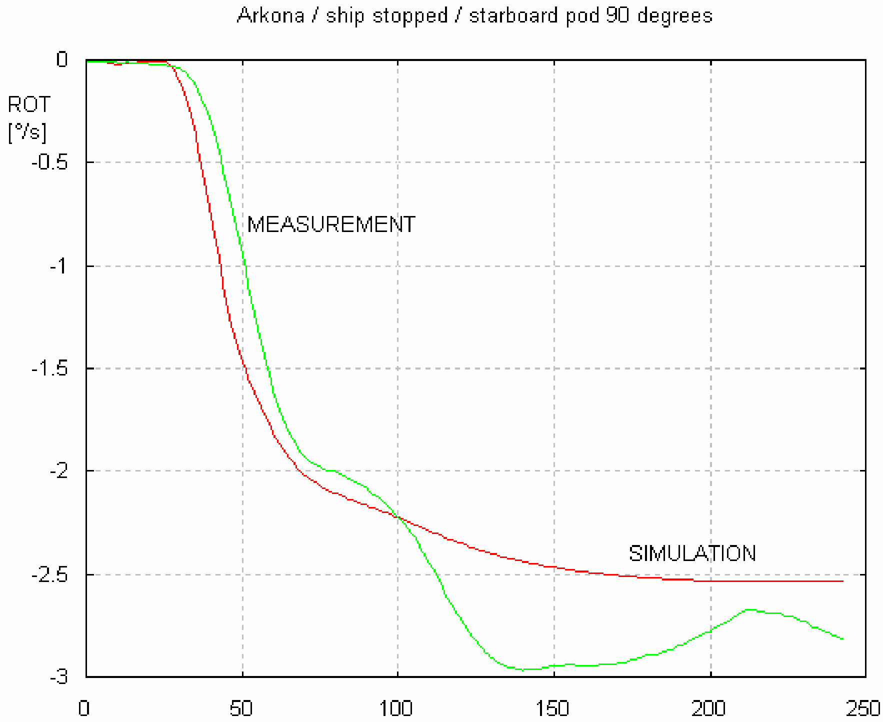


Fig.23.

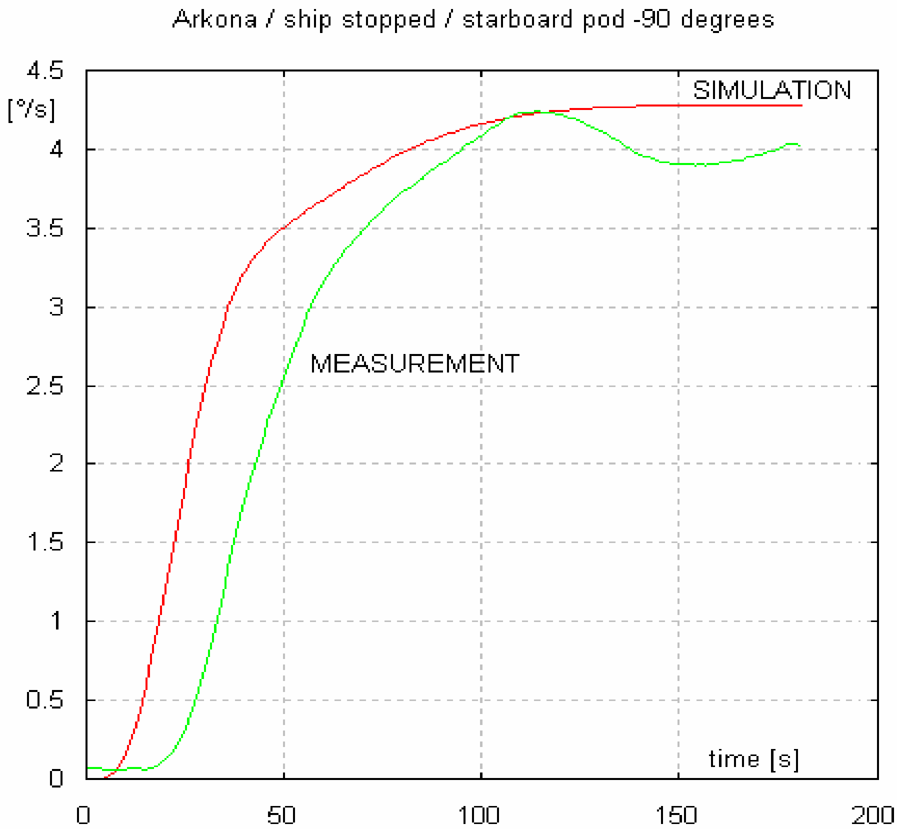


Fig: 24.

Fig. 24 taken from de Mello Petey (2008) paper, shows the comparison of a simulated manoeuvre versus the measurements with the only difference, being that this time the starboard POD was commanded to -90^0 creating thrust to port. In this case the propeller race was directed away from the ship and the result was that the thrust starboard was substantially higher.

A comparison of the simulation versus the measurements taken from the same reference, for the manoeuvre where the starboard POD is at an angle 45^0, so that in this case the POD race does not affect either the ship hull or the other POD is shown in Fig.25.

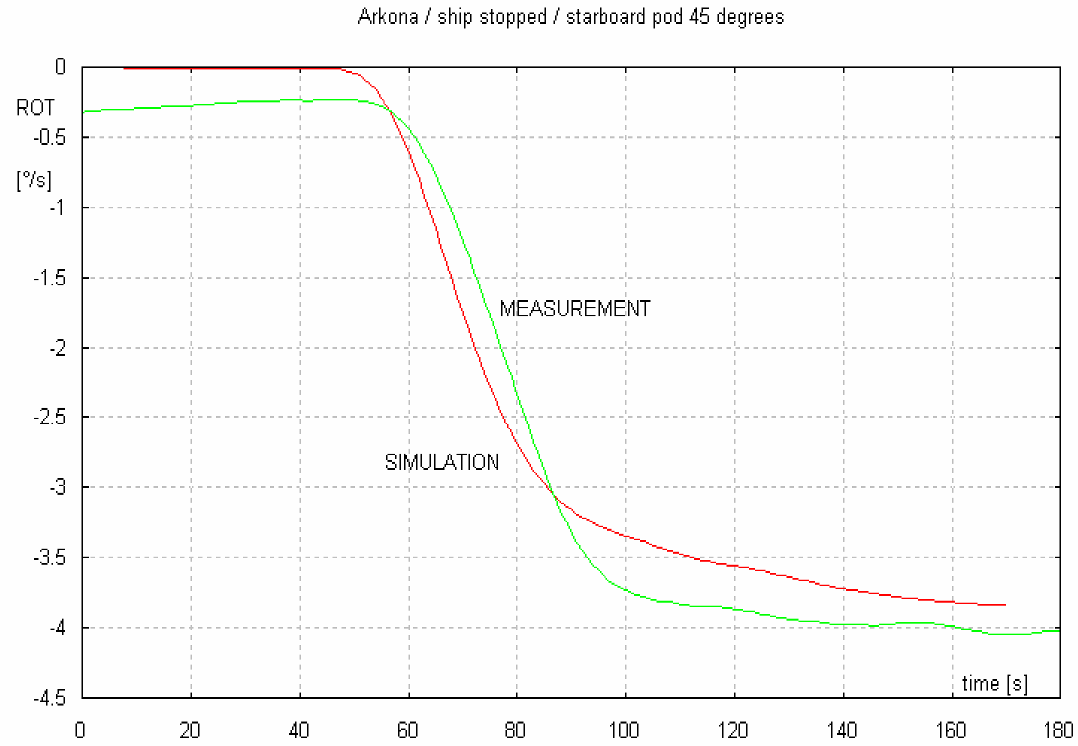


Fig: 25.

The above examples show a relatively good level of accuracy of the simulation program. In the simulation program local surge and sway velocities are obtained by adding the velocity of the propeller race to the local forward and lateral velocities due to ship motion. The velocity of propeller race is modelled in the simplified manner as a jet flow the direction of which is opposite to the thrust generated by POD. Test planned to validate simulation program referred to above were performed with the pollution control ship ARKONA of the length of 69.2m propelled by two POD units type SEP2 (Schottel Electric Propulsion).

1.2 Survey of interactions between azimuthing control devices and the ship hull

Within this section of the task three problems are identified, these are;

- Problem of evaluation of wake and thrust deduction for ships fitted with azimuthing control devices;
- Problem of effect of stern design on manoeuvring qualities of ships fitted with azimuthing control devices; and
- Problem of interaction between PODs and the hull of the ship

Wake and thrust deduction (form coefficients) for ships fitted with azimuthing propellers

This first problem is related mainly to propulsive characteristics of POD driven ships as compared with conventional propulsion. It does not affect manoeuvring and ship handling characteristics. There are a number of papers dealing with this particular subject and some experimental data from towing tank tests is also available. The most comprehensive review of propulsive characteristic of pod driven ships including cavitation characteristics is contained in the report of the Specialist Committee on Azimuthing Podded Propulsion to 25th ITTC Conference (2008). This report also includes several useful references.

When simulating the manoeuvring characteristics of a ship fitted with podded propulsors it may also be important to estimate propulsive characteristics. These in turn require knowledge of wake and thrust coefficients for the particular ship. At present, the only way to accurately acquire information regarding the value of these coefficients is to perform model tests in a towing tank. There are no approximate formulae or data available for POD driven ships similar to those well known formulae based on systematic model tests for vessels with conventional propulsion. It still uncertain how the installation of a POD propulsion systems affects the wake coefficients of the hull, although the different form of the stern used when PODs are installed must influence the flow hence affecting nominal wake coefficients.

In this concept is discussed in a paper by; Ohashi, Hino (2004). In this paper some results of numerical simulation of flow around stern of the tanker that was fitted with tractor and pushing type of azimuthing propeller was reported. The wake coefficients and form factors for both versions were calculated and compared with measured values in the cavitation tunnel. This is shown in the Table 8.

	Measured		Computed	
	Pusher	Tractor	Pusher	Tractor
$1 + K$	1.1666	1.190	1.290	1.299
$1 - w_n$			0.777	0.724

Table 8: Comparison of form factor and nominal wake coefficient for azimuthing propulsors (Ohashi and Hino 2004)

The results show that for a tractor type, the wake coefficients are higher and form factors lower in comparison to pusher type propulsor what may be expected. However the difference between computed and measured values is rather high. Therefore is seems that the method which was employed is not yet sufficiently reliable and, as it has to be tested and developed further. Therefore no general conclusions can be drawn from this single test, while it does provide useful information on its own. The ITTC report (2008) recommended using the following calculations of form factor for a podded propulsor. The empirical formula proposed by Hoerner (1967) was derived for airships, as the form of POD nacelle resembles the form of that of an airship:

$$K_{BODY} = 1.\left(\frac{D}{L}\right)^{3/2} + \left(\frac{D}{L}\right)^{3}$$

Where: *L= POD length*
D= POD diameter

And resistance of POD body is equal then:

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

Where: S=wetted surface area
C_F=friction coefficient

There is also empirical formula derived by the same author for strut form factor:

$$K_{STRUT} = 2\delta_S + 60\left(\delta_S\right)^4$$

Where: δ_S =the average thickness ratio of the strut
S = wetted surface area of the strut

With the similar formula for strut drag.

A scheme for calculating the POD contribution of the manoeuvring derivatives for both stabilizing and control was proposed by; Woodward et al (2003). Strut lift, POD body interaction and propeller race effect were considered and finally relevant formulae were proposed for POD lift force, fin control contribution, side force due to inclination of the propeller plane and finally for POD control force.

The effect of stern design on manoeuvring qualities of ships fitted with azimuthing control devices

From the point of view of ship handling capabilities, simulator work and training has become a more important problem. The problem exists when simulating the effect of ship hull form and arrangement of appendages on manoeuvring characteristics of the ship fitted with azimuthing propulsors. At present (June 2010), there are rather few papers dealing with this subject. It appears that the most important problem is affect on manoeuvring due to the shape and arrangement of appendages, first is the affect of fins of different arrangement and proportions.

Tests have been performed with the purpose of investigating this effect on manoeuvring characteristics of cargo ships having large block coefficient fitted with POD propulsion were reported by Kobylinski (2004) and by Kobylinski & Nowicki (2005).The test were performed in open water (lake) and the model used for testing POD propulsion was manufactured in the *1:24* scale, of the vessel. The model representing a gas carrier, was fitted either with single pushing POD or twin PODs with pulling propellers. The experiments comprised *inter alia* standard manoeuvrability tests such as turning circle tests, pull-out tests and zig-zag tests.

Tests were performed following recommendation of IMO (2002), however the range of rudder (POD) angles was extended up to 90^0. All tests were executed at two approach speeds: 6 knots and or 14 knots corresponding to full scale. However, the approach velocity had very little effect on the results achieved. One version of the model with single POD and several versions of the model with twin PODs were tested. Table 9 shows the list of all model versions. Versions of the model fitted with two skegs are shown in Fig. 26, and Fig. 27 shows versions of the model with one central skeg.

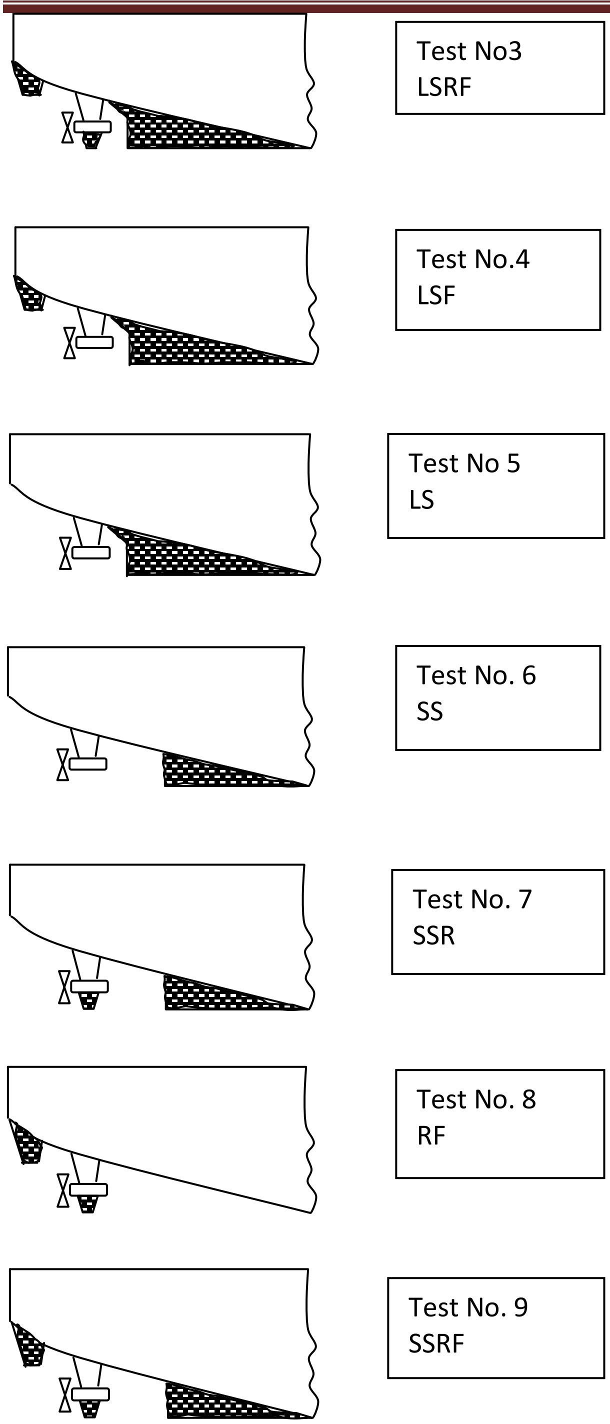


Fig. 26 Versions of the model with two POD's and two skegs

With single POD propulsion during standard *10/10 deg* tests because of a very high degree of dynamic instability model did not respond to counter rudder. In standard *20/20 deg* tests the first overshoot angles were extremely high, exceeding 120^0, the second were kept within limits of about 30^0. Additional *20/10 deg* tests revealed similar behaviour. Handling exercises where the model was sailing within limits of a narrow fairway making a loop confirmed the above conclusions.

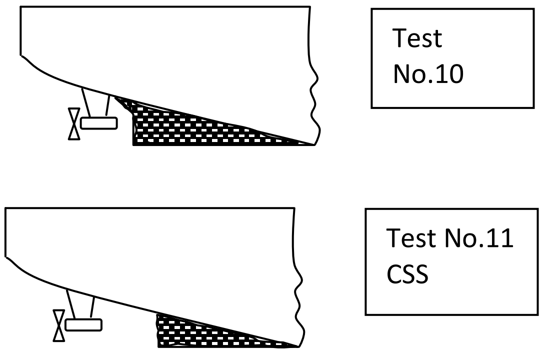


Fig 27. Versions of the model with two PODs and single central skeg

Steering of the model and keeping it within the limits of the fairway was very difficult, sometimes really impossible. Control of yawing was difficult and in order to counter turning large rudder angles were necessary. Clear passing a very narrow passage under the bridge was impossible in spite of very skilled pilot at helm. The judgement of pilots with respect of single POD propulsion was negative. It was concluded that single POD propulsion is not suitable and further tests of this version were cancelled.

Test	Description
1	Model with one POD
2	Two PODs, without skegs and fins
3	Two PODs, two large skegs rudder fins and stern fin
4	Two PODs, two large skegs, stern fin
5	Two PODs, two large skegs,
6	Two PODs, two small skegs
7	Two PODs two small skegs rudder fins
8	Two PODs, rudder fins, stern fin
9	Two PODs, two small skegs, rudder fins,stern fin
10	Two PODs, central large fin
11	Two PODs, central small fin

Table 9: Versions of the model tested (twin POD's)

The behaviour of the model fitted with twin PODs without fin, or with small central fin (e.g. tests No.10 and No. 11 - See Fig.27) was similar to the behaviour of the model with single POD, although dynamic stability in this condition was slightly better and in some *10/10 deg* tests model responded to counter rudder. With large central fin installed overshoot angles in *10/10 deg* tests were considerably smaller, although in most cases still much larger as required by IMO standard.

As it was expected, installation of fin caused increase of both tactical diameter and advance, but still turning ability was excellent. Installation of two skegs, each in front of the POD and in addition a combination of fins at stern and at PODs revealed important effect on manoeuvring characteristics of the model. Several variants were tested as shown in Fig.26 and in the Table 9. The behaviour of the model improved considerably. Turning ability characteristics for the model fitted with two PODs and different combinations of skegs and fins are shown in Fig. 28.

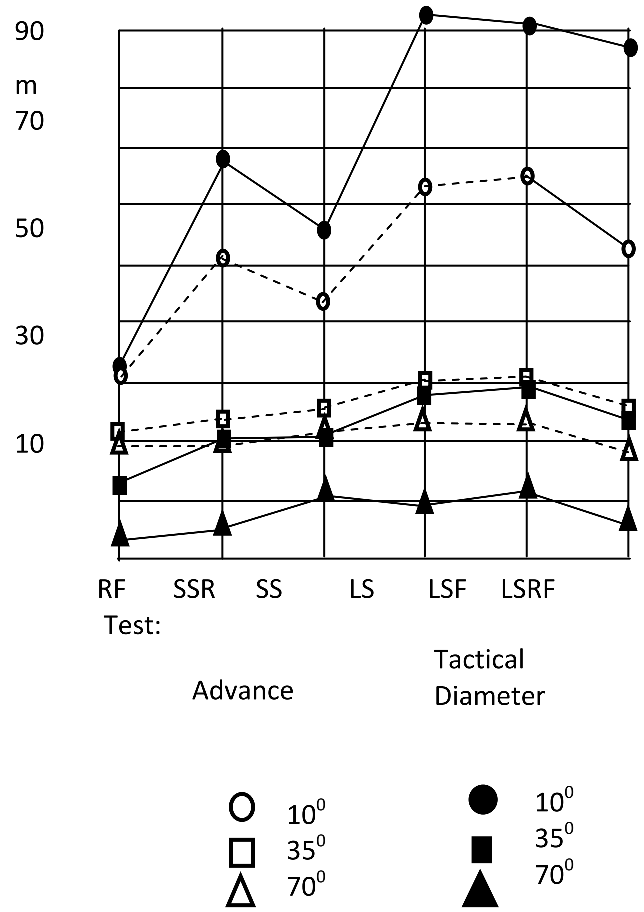


Fig. 28. Tactical diameters and advances at approach speed 14 knots

The example results of zig-zag tests for the model fitted with two PODs and different combinations of skegs and fins are shown in fig. 16. From Fig.28 may be seen that tactical diameter and advance for 35^0 rudder never exceeds 30m (2.6 L) and for 70^0 rudder are less than 2.0 L. Fig. 29 shows that for all versions tested except version where no skegs were installed first overshoot angles in *10/10 deg* test are within IMO limit. Handling of the model in the narrow fairway, negotiating the bends, entering the locks and harbour basins was easy and the model responded properly to counter rudder. Effect of skegs and fins is illustrated in Tables 10, 11, and 12.

As expected, reduction of the area of skegs resulted in improving of the turning characteristics at the same time making course keeping characteristics worse, although still within IMO limits. This effect is important as it may be seen from Table 10 (comparison of tests LS - large skeg and SS - small skeg). Reducing the size of skeg caused, for example, at 35^0 rudder and approach speed $v = 14$ knots reduction of tactical diameter from 37.9m to 20.1m (3.27L to 1.74L) with corresponding reduction of advance. At the same time 1^{st} overshoot angle in *10/10 zig-zag* test increased from 14.3 to 17.6 deg.

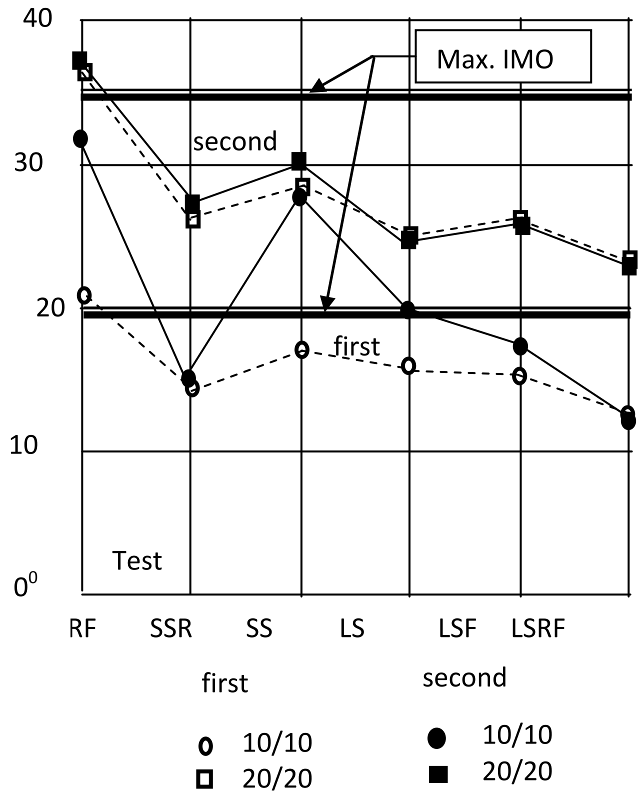


Fig. 29. Overshoot angles in zig-zag tests for approach speed 14 knots

Test		LS		SS	
Approach speed, knots		6	14	6	14
Advance, rudder 10^0		69.5	64.1	52.6	43.9
35^0		33.0	30.1	27.9	26.6
70^0		25.5	23.1	22.5	22.0
Tact.diam. rudder 10^0		90.9	94.1	62.3	56.2
35^0		30.7	37.9	22.3	20.1
70^0		11.9	9.4	9.4	11.1
Overshoot angles	10/10, 1st	15.0	16.0	21.1	17.6
	2nd	16.8	20.0	26.5	27.0
	20/20, 1st	25.0	25.7	29.9	28.4
	2nd	26.3	25.4	31.2	30.0

Table 10: Effect of size of skegs

Installation of small fin in the lower part of the POD propeller resulted in improving the turning characteristics as well as course keeping characteristics. The effect of this fin is important as it may be seen from Table 11 (comparison of tests SS – without fin and SSR – with fin). The tactical diameter and advance at *35^0* rudder were almost the same, but overshoot angles were much smaller (1st overshoot angle at 14 knots approach speed in *10/10 zig-zag* test drops from 17.6 to 14.3 deg).

It may be expected that the installation of a small fin at stern may improve course keeping ability considerably. In fact, it had little effect as it is seen from Table 12 (comparison of tests

LS – without fin and LSF – with fin). With slightly worse turning ability the course keeping ability, measured by overshoot angles remained almost the same.

It may be concluded that with two PODs installed course keeping ability is much better, however in order to achieve satisfactory results it would be necessary to fit a combination of skegs and fins, to the vessel. Consideration of these issues properly at the design stages, will allow the vessel to achieve good course keeping and excellent turning characteristics.

Test		SSR		SS	
Approach speed, knots		6	14	6	14
Advance, rudder 10^0		46.3	50.2	52.6	43.9
35^0		22.6	24.7	27.9	26.6
70^0		16.4	19.9	22.5	22.0
Tact.diam. rudder 10^0		63.4	68.1	62.3	56.2
35^0		20.4	20.6	22.3	20.1
70^0		3.55	6.4	9.4	11.1
Overshoot angles	10/10, 1st	13.5	14.3	21.1	17.6
	2nd	13.3	15.4	26.5	27.0
	20/20, 1st	25.5	26.2	29.9	28.4
	2nd	25.6	26.6	31.2	30.0

Table 11: Effect of rudder fin

Test		LS		LSF	
Approach speed, knots		6	14	6	14
Advance, rudder 10^0		69.5	64.1	63.4	65.4
35^0		33.0	30.1	35.9	31.5
70^0		25.5	23.1	28.0	22.9
Tact.diam. rudder 10^0		90.9	94.1	85.0	90.6
35^0		30.7	37.9	31.2	30.5
70^0		11.9	9.4	17.5	11.4
Overshoot angles	10/10, 1st	15.0	16.0	15.4	15.7
	2nd	16.8	20.0	17.5	17.3
	20/20, 1st	25.0	25.7	27.9	26.3
	2nd	26.3	25.4	27.5	25.9

Table 12: Effect of the stern fin

The measurements taken of the tactical diameter, advance and overshoot angles provide good material for assessment of manoeuvring characteristics and in particular they enable checking whether the design satisfies criteria set up by IMO (2002). However, the results of these measurements is not sufficient for the evaluation of the handling potential of the ship in various external conditions. The effect of centre skeg was tested by Haraguchi (2003). In general effect of the centre skeg was reducing the width of loop in spiral tests and therefore improving course-keeping ability. This confirms conclusions drawn from the tests discussed above.

Interaction between the pods and the hull of the ship

Pod-hull interaction was considered by de Mello Petey (2008). Fig.30 was taken from this source and shows schematically the stern of the ship when one of the PODs is used in soft mode.

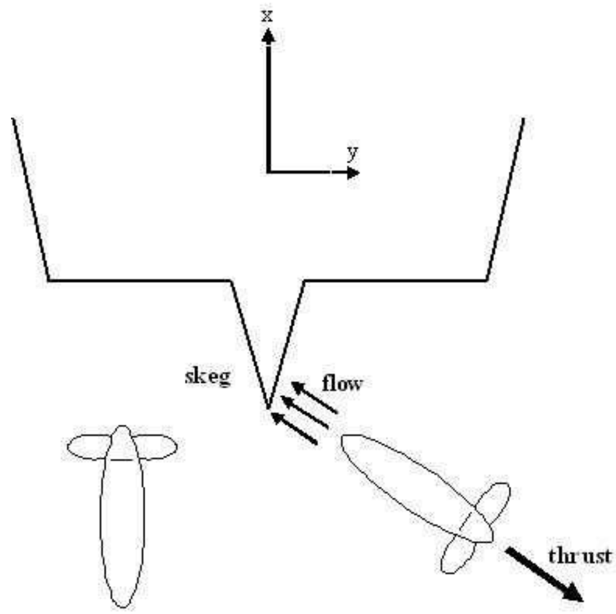


Fig.30. POD working in the soft mode showing the effect of hull=POD interaction

In the position of the starboard POD as shown in the Fig.30, POD propeller race that is directed against skeg generates force opposing the propeller thrust. In some cases the opposing thrust might reduce POD thrust to zero, so that is not turning at all. This effect must be taken into account when developing mathematical model. The author claims that in the simulation module for podded propelled ships ANS 5000 this effect is taken into account.

Conclusion

The results of the survey shows that interaction between two or more podded propulsors is important and it may affect the manoeuvring characteristics of a vessel in certain modes of control. It may also have a considerable affect in certain situations. However in part of the simplified method described in one publication, there is a general lack of data concerning this effect. And as yet it is not known if, and how, this effect is taken into account in computer programs used in real time simulator facilities. When using large manned models for training this effect is automatically taken into account. However the effect of scaling down propellers on the interaction is not known and there are no indications how it may influence manoeuvrability.

More data is available on the interaction between a POD and the form of ship‟s hull, in particular on the effect of skegs and fins. It appears that skegs and fins affect the manoeuvrability considerably. First of all their effect is most visible on dynamic stability. There is a general tendency that ships equipped with one POD are dynamically very unstable, the same happens with ships equipped with two PODs. it should be noted that this is without skegs, fins, or small fins installed. The installation of skegs and fins improves dynamic stability, however at the same time making the turning ability characteristics slightly worse. How this effect is taken into account in mathematical models is uncertain, but some data from experiments with ship model tested without skegs or fins. Or models tested with skegs or fins of different sizes installed is available and may be used.

Data on wake and form coefficients for ships with podded propulsors currently cannot be found in publications. But such data are certainly available as a result of model tests performed in towing tanks when testing ship models for shipyards. There is a problem of evaluation of these coefficients as it is not relevant to the facilities using manned model for training.

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6. APPENDIX A: ALTERNATIVE CALCULATION OF FLOW STRAIGHTENING EFFECTS

The present Rembrandt model takes account of hull flow straightening effects when calculating the rudder inflow velocity, but not when calculating propeller inflow velocity. In order to keep backward compatibility while also allowing for the different flow straightening effects expected from the open sterns used in podded ships, the flow straightening effects of the hull will now be definable for each component (including props)

Hence, allowing for straightening:

$$u_{11} = u_{10}\frac{\cos\alpha}{\cos\alpha_1}$$

$$v_{11} = v_{10}\frac{\sin\alpha}{\sin\alpha_1}$$

Where:

$$\alpha_1 = a\tan\left(\frac{v_{10}}{u_{10}}\right)$$

$$\alpha = \alpha_1\left[k + (1-k)(1-\cos\alpha_1)\right] \ : \ \text{for } |\alpha_1| < 90^0$$

$$\alpha = \alpha_1 \qquad : \ \text{for } |\alpha_1| \geq 90^0$$

Where θ = pod azimuth angle (positive to port) and α is the pod angle of attack. k = flow straightening factor (usually set to 0.55 for conventionally propelled ships in Rembrandt).

Next we must add the wake velocity of any upstream pods if applicable:

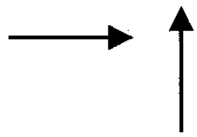
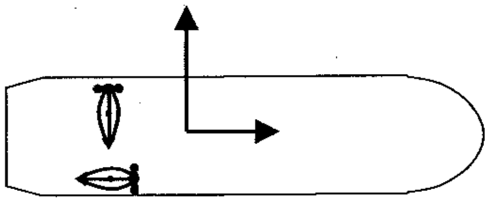
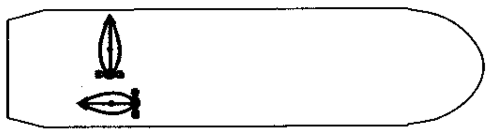
$$u_1 = u_{11} + v_{jeff}\cos\theta_i$$

$$v_1 = v_{11} + v_{jeff}\sin\theta_i$$

Where θ_i = upstream pod (or prop) azimuth angle (positive to port).

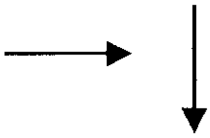
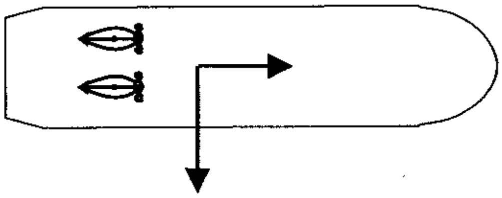
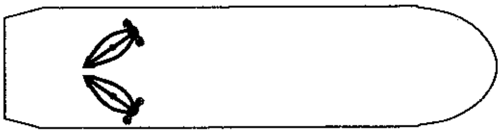
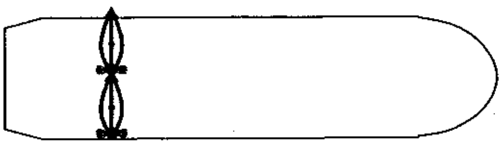
7. APPENDIX B: ESTIMATED POD EFFICIENCY FOR A SHIP EQUIPPED WITH TWO PODS AS A FUNCTION OF POD POSITION DUE TO THE HYDRODYNAMIC INTERACTION BETWEEN PODS AND SHIP HULL AND FLOW STRAIGHTENING EFFECTS.

The following tables illustrate **approximate** pod efficiency values for lateral movement with one pod perpendicular to the vessel's centerline. These values are for a typical large cruise vessel whose initial speed is 0. Fx is fore and aft movement, Fy is lateral movement. The vessel's stern is moving to port.

Pod Position	Port	Stbd	Fx	Fy
				
	-90	0	100%	80%
	+90	0	100%	50%
	0	-90	100%	100%
	0	+90	100%	80%

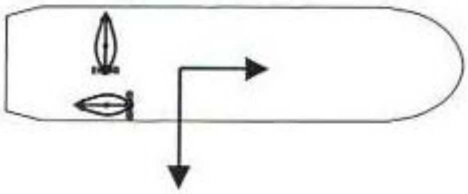
Azimuth Pod Propulsion and Ship Maneuvering Simulations

The following tables illustrate **approximate** pod efficiency values for lateral movement using a combination of azimuth angle and RPM to produce lateral movement. These values are for a typical large cruise vessel whose initial speed is 0. Fx is fore and aft movement, Fy is lateral movement. The vessel's stern is moving to starboard.

Pod Position	Port	Stbd	Fx	Fy
				
	0	0	200%	0
	+135	+45	0%	140%
	-45	+45	20%	120%
	+90	+ 90	0	150%

Azimuth Pod Propulsion and Ship Maneuvering Simulations

The following tables illustrate **approximate** pod efficiency values for lateral movement with one pod perpendicular to the vessel's centerline. These values are for a typical large cruise vessel whose initial speed is 0. Fx is fore and aft movement, Fy is lateral movement. The vessel's stern is moving to starboard.

Pod Position	Port	Stbd	Fx	Fy
	+90	0	100%	100%
	-90	0	100%	80%
	0	+90	100%	80%
	0	-90	100%	50%

Azimuth Pod Propulsion and Ship Maneuvering Simulations

V. Ankudinov, TL & L. Kobylinski, SRTC