The Specialist Committee on Azimuthing Podded Propulsion

Final Report and Recommendations to the 24th ITTC

1. INTRODUCTION

1.1 Membership

The 23rd ITTC appointed the Specialist Committee on Azimuthing Podded Propulsion with the following Membership:

- Professor Mehmet Atlar (Chairman). University of Newcastle upon Tyne, United Kingdom.
- Dr. Pengfei Liu (Secretary). National Research Council Canada, Canada.
- Ir. Jaap H. Allema. Maritime Research Institute Netherlands, The Netherlands.
- Mr. Satoru Ishikawa. Mitsubishi Heavy Industries Ltd., Japan.
- Dr. Se-Eun Kim. Samsung Heavy Industries Co. Ltd., Korea.
- Dr. Alexander V. Poustoshniy. Krylov Shipbuilding Research Institute, Russia.
- Dr. Antonio Sanchez-Caja. VTT Industrial Systems, Finland.
- Dr. Noriyuki Sasaki. Sumitomo Heavy Industries ltd., Japan.
- Dr. Antonio Traverso. Centro per gli Studi di Tecnica Navale, Italy.

1.2 Meetings

At the first meeting of the Committee, Dr. Pengfei Liu was elected as Secretary of the Committee. Four formal meetings of the Committee were held as follows:

- Newcastle upon Tyne, United Kingdom, November 2002.
- Genova, Italy, October 2003.
- St John's Newfoundland, Canada, August 2004.
- Wageningen, The Netherlands, January and February 2005.

2. RECOMMENDATIONS OF THE 23rd ITTC

1. Review and make improvements to the Procedures 7.5-02-03-01.3 for podded propulsor tests and extrapolation.
2. Recommend procedures for carrying out podded propulsor cavitation experiments
3. Establish guidelines for extrapolation to full-scale.
4. Review impact on off-design conditions to loads and stability.
5. Review impact on IMO manoeuvring criteria.

3. FOREWORD

3.1 General Remarks

The last decade has witnessed a growing uptake of integrated electric azimuthing podded propulsors. Since commercial introduction in the early 90s, the range of application, capacity and type has increased tremendously. By mid-2004, 45 pod-driven ships were reported in operation with 27 more on order (van Blarcom et al., 2004). Averaging two pods per ship, pod power ranges from 2 to 20MW offering speeds up to 25kts; notwithstanding, the new trans-atlantic liner *Queen Mary 2 (QM2)* has four 21.5MW pods and a design speed of 30kts. Other benchmark applications include the World's two largest icebreakers, *Tempera* and *Mastera* (DWT 106K each) based on the Double Acting Tanker (DAT) principle. Further, 2004 saw the delivery of the world's first two Hybrid CRP-Pod driven fast Ropax ferries, *Hamanasu* and *Akashia*; both capable of 32kts.

In addition, various high profile Research & Technical Development (RTD) projects have been conducted under the European Framework Programme (FP), while 2004 saw the first international conference dedicated to pod propulsion technology (T-POD). Also, following the proposal for an interim procedure for predicting podded propulsor-driven ship performance (ITTC, 2002c), the 23rd ITTC established this Specialist Committee.

During the summer 2004 the Committee received a letter from a prominent pod manufacturer, identifying a significant knowledge gap with regard to extrapolation to full-scale; issues that were already included in the Committee's tasks (Mattila and Veikonheimo, 2004). The letter expresses great interest in the Committee's work and offers information related to hydrodynamic testing and design experience attained by this company. Particular emphasis is given to the use of different scaling methods of pod-housing drag and unit open water performance estimations. As included in this letter, Fig. 3.1 gives comparison of the podded propulsor (unit) efficiency in open water using two different scaling methodologies. It is emphasised that the situation should be even more complex when the differences between model basins and testing methods are considered.

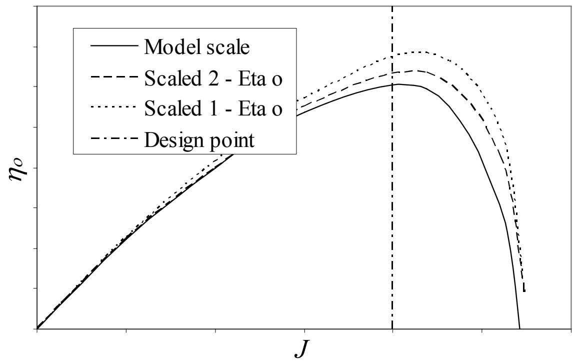

Figure 3.1- The comparison of full-scale pod unit efficiencies from two different basins based on the same model scale value.

The letter claims these contradictions (a difference of up to 6.4% at design point) having 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.

3.2 Report Layout

From herein, the report content is as follows:

- Section 4: State-of-the-art review
- Section 5: Podded propulsor tests and extrapolations (Task 1)
- Section 6: Guidelines on extrapolation to full-scale (Task 3)
- Section 7: Procedures for model-scale cavitation experiments (Task 2)
- Section 8: Impact of off-design conditions on loads and stability (Task 4)
- Section 9: Impact on IMO Manoeuvring Criteria (Task 5)

- Section 10: Special applications for podded propulsion
- Section 11: Technical conclusions
- Section 12: References
- Appendix A: Improved Draft Procedures for podded propulsor tests and extrapolation.

Finally a new set of Procedures for model scale-cavitation tests (7.5-02-03-03.5), which is reviewed in Section 7, is submitted to the 24th ITTC Quality Systems Group to be included in the ITTC Recommended Procedures, as part of this Committee's work (ITTC, 2005).

4. STATE-OF-THE-ART REVIEW

4.1 Research and Development Activities

Recent years have witnessed a number of high profile national and multi-national R&D projects concerning various aspects of pod propulsion. In this section, and within the framework of this Committee's tasks, a short review of R&D projects worldwide is made.

Between 1999 and 2005, three large scale research projects have been carried out under the EC Framework Programme (FP5). First, *OPTIPOD* brought together 14 EU partners to establish design guidelines for pod-driven ships; in particular, issues regarding IMO criteria were addressed (OPTIPOD, 1999). Next, *PODS-in- Service* brought together 18 partners to investigate the reliability of pods through in-service monitoring and measurement (PODS in Service, 1999). Finally, *FASTPOD* brought together 17 partners aiming to identify the maximum feasible limits when using podded propulsors on large and fast commercial ships in an efficient, safe and environmentally friendly manner.

Regarding disseminations from the above projects, there has been reasonable publications from the OPTIPOD and FASTPOD projects whereas there is hardly any publication from PODS-in-Service; due to strict commercial confidentiality.

Outside Europe, a 5 year national research programme, entitled "Systematic Investigation of Azimuthing Podded Propeller Performance", was started in 2002 in Canada. This research programme aims to: quantify the effect of podded propulsor configuration on performance; develop computational methods for performance prediction; develop an extrapolation method for power prediction; quantify the blade loading effects in open water and in ice at off-design conditions; develop new instrumentation for performance evaluation; develop speciality manufacturing capability for high quality model propulsors.

In the above project several hydrodynamic design issues and problems have been addressed and investigated including: (1) Systematic design data on geometric variation of pod housing at model scale and to develop a reliable method measuring the drag on a pod (Molloy et al., 2004); (2) The cause of puller-type propeller to have a better efficiency than its pusher-type counterpart in atmospheric and cavitating conditions (Islam et al., 2005a and 2005b), respectively; (3) The effect of pod and strut on propulsive performance using numerical and experimental methods (Islam et al., 2005c); (4) An experimental and numerical investigation on the blade shed vortex impingement on strut and pod (He et al., 2005).

In Japan, in order to address the land bound transport problems and the emission demands of the Kyoto Protocol, a national research programme, entitled *Super-Ecoship*, was initiated. To promote cargo transportation from land to sea, this project aims to develop novel coastal ships driven by CRP-Podded propulsor with a higher cargo capacity, propulsive efficiency, manoeuvrability and less vibration and noise. CRP-Podded propulsor, in this case, refers to a pair of contra-rotating propeller at one end of the pod (RINA, 2005).

In Finland the *ENVIROPAX* project, investigated the Hybrid CRP-Podded propulsor concept and various hydrodynamic issues; power split; propeller design; powering performance evaluation (Varis, 2005). One of the major outcomes of this research programme was the realisation of the world's first two Hybrid CRP-Podded propulsor driven Ropax ferries built in 2004.

Also, there are some high profile research projects ongoing in USA regarding new electric motors. In order to address the US Navy's pursuit of an Integrated Power System (IPS), or electric drive, for its future surface combatant fleet, numerous projects have been sponsored to develop high power density permanent magnets and high temperature super-conducting motors, e.g. (Bretz, 2004).

Within the same field but with commercial objectives, a permanent magnet Rim-Drive pod (RDP) has been developed by a prominent electric motor company. It was reported (Van Blarcom, 2004) that a 1.6 MW RDP was tested successfully in-air and is due in service in 2006.

These motor technologies will have an impact on the size and shape of the pods and thus future ITTC activities.

4.2 Conferences and International Events

As part of the FP5 project FASTPOD and this Committee's activities the conference "First International Conference on Technological Advances in Podded Propulsion" (T-POD) was held in Newcastle University in 2004; (Atlar et al., 2004). T-POD attracted 120 delegates, 37 technical papers and brought together for the first time major pod manufacturers, shipyards, operators, designers, test facilities, classification societies, regulatory authorities, researchers and academicians related to this technology. Most of the papers presented at T-POD were directly related to the Committee's tasks; Committee Members also presented papers cited and discussed in this report where appropriate.

There have also been other international events where a limited amount of dissemination can be found regarding to pod propulsion; viz: PRADS'01; HIPER'02; FAST'03; PRADS'04; ONR'04, FAST'05.

4.3 Landmark Applications for Podded Propulsion

In recent years some landmark applications for podded propulsion have taken place.

Two Double Acting Tankers (DAT) *Tempera* and *Mastera*, were delivered in 2002/3. These two large Aframax ships are the first crude carriers built according to the DAT principle. Propulsion for the DAT is provided by a puller-type unit with a fixed pitch ice class propeller. The podded propulsor has a maximum rating of 16MW providing each vessel with a speed of 16.5kts fully loaded in open water. Also, when in ice, the tankers are capable of advancing at more than 7kts in 1m thick ice (Sasaki et al., 2004).

The world largest passenger liner *QM2* delivered in 2003. The ship is propelled by four podded drives (two fixed and two azimuthing) achieving a service speed of 26.5kts and a top speed of 29.35 kts (RINA, 2004). The optimum location of the front and rear pods as well as the tilt angle of the pods and their neutral steering angle were deter-mined based on propulsion optimisation tests. During the course of the project, various combinations of direction of rotation of the front and rear propellers were tested for the effects on performance as well as on propeller induced hull pressure fluctuations. Moreover, based on the test results, the arrangement of the pods was adjusted and the pods redesigned to increase the distance to the hull; with enlarged strut length. The final pod configuration in terms of selected positions, best propeller design, best propeller direction of rotation and propeller tip-hull clearances was selected as the best solution from both a powering and a vibration excitation point of view.

Two fast Ropax ferries, *Hamanasu* and *Akashia*, driven by the world's first Hybrid CRP-Podded propulsion system were delivered in 2004. A total power of 52.36MW drives a 5 bladed CPP via conventional drive and a pulling type fully azimuthing unit (17.6MW) fitted with 4 bladed fixed pitch propeller in a CRP mode. The distribution of the total thrust between the CPP and the pod propulsor is 55% and 45%, absorbed at 150 and 170 rpm, respectively. This hybrid CRP-Podded drive system provided these ships with a service speed is 30.5 kts and a maximum trial speed of 32.04kts; (Ueda et al., 2004); (Varis, 2005); Bushkovsky et al., 2004)

5. TESTING AND EXTRAPOLATION

This section presents a review of the improved Procedures (7.5-02-03-01.3) recommended by the Committee which is included in Appendix A within more details.

5.1 Podded Propulsor Testing

Model tests are necessary to identify the calm water speed-power relation with the highest possible accuracy. Such tests can be divided into propeller and podded propulsor open water tests and (self-) propulsion tests; (ITTC, 2002e). The basic open water and propulsion tests are already established for conventional propellers, but for podded propulsors there are some special issues and complications which are discussed herein.

5.2 Propeller Open Water Test

The procedures for podded drive propeller open water tests are basically the same as the procedures for conventional open water tests, (ITTC, 2002b). However, some aspects for propellers with strongly tapered hubs are not considered there and they are discussed in this section.

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 poorly faired transition from hub to aft fairing will introduce flow separation which will affect the measured propeller performance. An example of aft fairing is shown in Fig. 5.1.

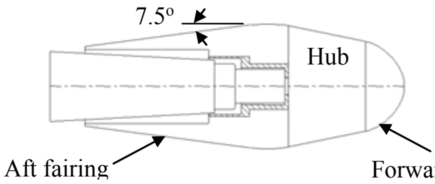

Figure 5.1- Hub geometry for an open water test with a puller-type propeller.

In the case where the aft fairing rotates with the propeller, a separate pre-test should be performed on a similar set-up but with the propeller replaced by a dummy hub. This is 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, one obtains 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 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 podded propulsor performance.

In the case where the aft fairing does not rotate with the propeller, 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 aft fairing method can provide useful knowledge of the effects of the pod-housing on the propellers performance. Generally speaking, the rotating aft fairing method is preferred.

5.3 Podded Propulsor Open Water Test

Podded propulsor open water tests are required when considering the complete pod unit (propeller; lower part of the pod, housing the motor (i.e. nacelle); upper part of the pod (i.e. strut); fin) as the propulsor, as recommended by the Committee.

A basic device can be used to achieve a podded propulsor 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.

The design and manufacture of a recent special pod model device is described in the open literature; (MacNeil et al., 2004). This device includes instrumentation for the measurement of propeller thrust and torque near the propeller hub, the total unit-thrust and pressures in the propeller hub gap. The device is intended for the systematic investigation of propeller pod-housing interaction, propeller hub gap effects and pod-housing design.

A point of special concern on pod models is 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.

For podded propulsor open water tests, a special test set-up is required. The recommended test configuration is shown in Fig. 5.2. This configuration contains the basic pod device with shells (i.e. pod-housing) and a lengthened vertical drive shaft for sufficient propeller submergence. A streamlined body is fitted around the drive shaft for two reasons to:

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

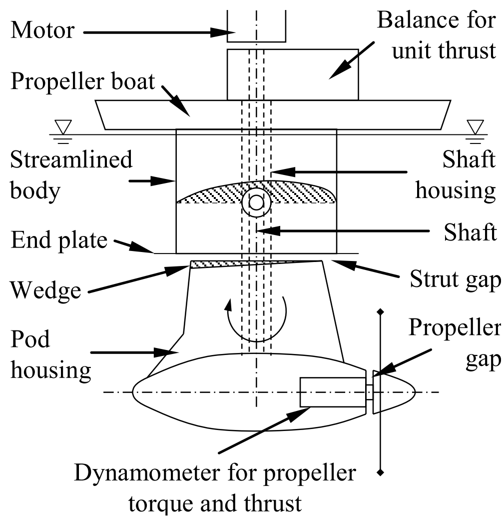

Figure 5.2- Podded propulsor in open water test set-up.

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

Propeller Gap Effect. 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 currently unclear.

Measurements are reported (Mewis, 2001), regarding the effect of the propeller gap width on the propeller and on the pod open water performance. In another study (Rijsbergen and Holtrop, 2004), similar gap effects were found; shown in Fig. 5.3. However, details are given for a new 5-components balance system for podded propulsor open water tests (Ukon et al., 2003) and include a parametric investigation on the propeller gap effect.

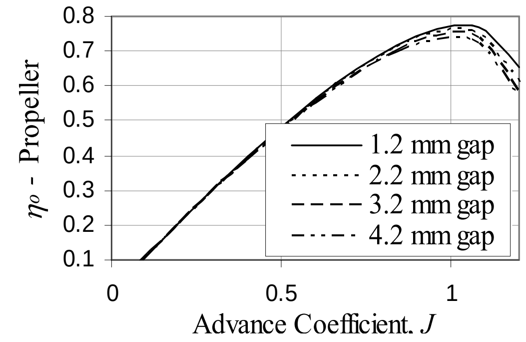

Figure 5.3- Open water characteristics of a puller-type pod based on thrust for different propeller gap widths.

Strangely, these results showed hardly any noticeable gap effect; which is in contradiction with the two other mentioned investigations. The reason for this deviation is not clear. Details of the propellers used by (Mewis, 2001) and (Ukon et al., 2003) are given in Table 5.1.

Table 5.1- Model Propeller Particulars.

Particulars	Mewis	Ukon et al.
Diameter (mm)	215.15	200.00
Pitch ratio	1.104	0.800
BAR (expanded)	0.58	0.55
Boss ratio	0.276	0.280
Blade number	4	4
Rot. direction	-	Right

Two of the three above-mentioned 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 uncertain 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 possibly affected propel-ler thrust measurement, the gap effect may not be an immediate obstacle for power prediction.

However, the propulsion factors, particularly the wake fraction obtained from a propeller thrust identity, can be important for the propeller design. This parameter will not only be affected by the gap effect itself as described above, but will also be affected if the gap widths are considerably different in the pod open water test and pod propulsion test. This is illustrated in Fig. 5.4 by the results of a thrust identity analysis conducted based on the data obtained from the above mentioned investigations where the main particulars of the propellers are close; as listed in Table 5.1. The error for the wake fraction determination will result in approximately 1% difference for the design pitch of the propeller.

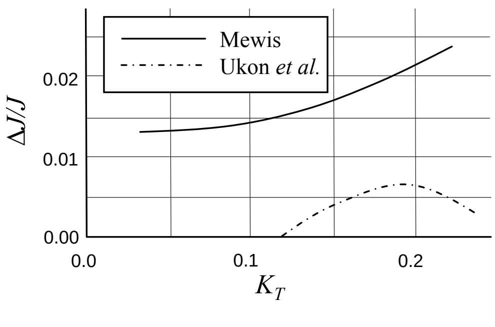

Figure 5.4- Potential error due to gap effect on propeller design condition (in association with wake fraction).

From the above, it is concluded that the performance of a puller-type propeller can 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. It is noted that, this matter is of utmost importance for the propeller design.

Strut Gap Effect. There is also a 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. However, the effect of this gap on the pod performance is considered to be quite small as shown in Fig 5.5; (Mewis, 2001).

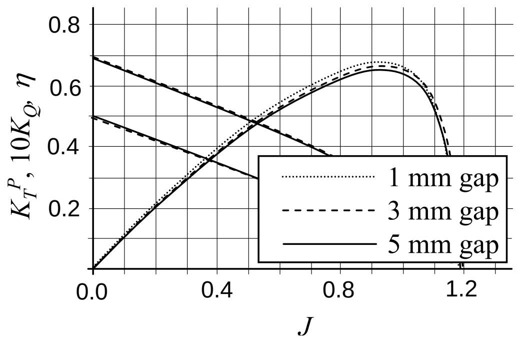

Figure 5.5- Effect of strut gap on pod open water characteristics, based on measured thrust of the unit for different strut gap widths.

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.

Also, the propeller shaft must be set in horizontal position during the open water tests. If the strut, in this position, has an inclined top section, it is advisable to make it horizontal by adding a wedge at the top. 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. It can even be considered to make the top section horizontal by taking away a small wedge and adding another small wedge, thus keeping the wetted surface area constant, although this will require the restoration of the original top section for model self-propulsion tests.

The podded propulsor open water test should 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. One approach is to use the method proposed in the ITTC-78 extrapolation procedure. The drag of the model pod-housing should be corrected according to the method described in Section 6. This will give the full-scale unit-thrust $T^{unit\text{-}0}$, as well as the matching full-scale unit efficiency $\eta^{\ unit\text{-}0}$.

Streamlined Body Effect. If the streamlined body shape is not similar to the strut shape, unknown 3-dimensional flow effects may occur.

To prevent 3-D 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 streamlined 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.

5.4 Podded Propulsor Propulsion Test

Podded propulsor (self-) propulsion tests are required for predicting the ships calm water performance with the best possible accuracy. Mainly, two methods are 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 (t, w and η_R).

The second method regards the total pod unit as the propulsion unit. This requires a pod open water test, a resistance test (without the pods) and a self-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.

Nakatake et al. (2004) presented a study on model propulsion test for a twin pod-driven bulk carrier. He tested several puller- and pusher-type pods and analysed the results by means of both indicated methods. Results showed that, although the power predictions for both methods were quite close, the propulsion factors of both methods differed considerably.

In podded 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 F, contains only the model friction correction force F_D, then the unit-thrust is correctly scaled and can be extrapolated to full-scale by means of $\lambda^3\rho_s/\rho_m$. 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 F, also contains the housing drag correction ($F_D^{housing}$), 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. [Note here *housing* applies to entire pod shell surface except the propeller]. Now, however, the unit-thrust is too low, due to excessive housing drag, and thus the unit-thrust needs to be corrected before extrapo-lating 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.

5.5 Extrapolation Procedure

This section only deals with the extrapolation of results from open water tests on propellers and podded propulsors. The extrapolation of propulsion tests is treated in Section 6.

Results of open water tests on propellers alone are treated in the same way as for conventional propellers; (ITTC, 2002b). However, for a pulling-type propeller it is recommended that the effects of the hub-taper and propeller gap can be cancelled by conducting dummy hub runs to correct the open water test results; thus determining only the propeller blade open water performance.

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 the 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 (T^{unit}) and the propeller blade thrust (T) and torque (Q^{unit}) are used to create the well-known open water table and diagram, expressing $K_T{}^{unit\text{-}0}$, $K_T{}^{0}$ and $K_Q{}^{unit\text{-}0}$, as a function of advance coefficient, $J=V_A/nD$. $K_T{}^{unit}$ as measured has to be corrected for the scale effects on the pod-housing drag. The pod housing drag correction ($F_D{}^{housing}$) has to be determined and should be added in non-dimensional form ($\Delta K_T{}^{housing}$) to the measured $K_T{}^{unit}{}_M$ values, to result in a $K_T{}^{unit\text{-}0}{}_S(J)$ curve for the full-scale.

5.6 Concluding Remarks

Podded propulsor 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.

Finally, the Committee recommends that the procedures reviewed in this section (Section 5) and the guidelines for the power-speed prediction, which is presented in Section 6, are strictly applicable to ships with a single pod and twin pods. The Committee recognise the importance of multi-pod applications on high-powered vessels (such as QM2 with 4 pods) which has emerged during the course of this Committee's work. This application would require special care in terms of wake treatment and propulsion tests as well as requiring full-scale data for validation of the applied procedures although the methods presented are generic in principle.

6. GUIDELINES ON EXTRAPOLATION TO FULL-SCALE

6.1 Speed-Power Extrapolation Procedure

The reference extrapolation procedure that this Committee recommends in Appendix A, (Section A.3) is based on a method similar to the ITTC-78 Procedure. The pod-unit with its housing replaces the single propeller in the procedure. Resistance, open water and self-propulsion tests are the basis for the extrapolation. Furthermore, the method, in its present state, is applicable to vessels with single and twin podded propulsors.

Resistance tests are conducted without the pod unit as if the extrapolation were made for conventional propellers. Open water tests are required for the complete pod-unit and are optional for the single propeller. The presence of the pod-housing makes the propeller thrust and torque in the podded propulsor different from those that would result from a propeller open water tests. By means of the optional tests additional information could be provided to the propeller designer on the wake induced by the pod-housing. Propulsion tests are performed by applying to the carriage a suitable towing force; of which the magnitude will be discussed later in Section 6.2.

In the pod unit open water and self-propulsion tests the unit-thrust is defined as the propeller thrust minus the drag of the pod-housing, and the unit-torque is the propeller torque. The housing drag is a quantity not easy to determine since it is calculated as the difference between two large quantities: the unit-thrust and the propeller-thrust. Additionally the propeller-thrust is not easily measurable because of hub-gap effects. Such effects will influence the prediction of the wake fraction induced by the pod-housing at the propeller plane, which is of interest mainly to the propeller designer. As discussed in Section 5.3, the gap effect is an important issue and currently there is no clear guidance how to control it. However, the dependency on this effect can be avoided in the calculation of the wake fraction induced by the housing using the K_Q identity.

Concerning the scaling of the pod-unit open water test results for a puller-type pod, two main corrections are necessary: one for the additional frictional forces on the model-scale blades relative to full-scale; the other for additional pod-housing drag in model-scale. The blade correction is based on the "*Lerbs*" equivalent profile method and follows the standard ITTC-78 Procedure. The correction to pod-housing drag is discussed in Section 6.3. The wake at the propeller plane induced by the pod-housing is not expected to be subject to any noticeable scale effect due to its pressure-based potential-flow nature. Consequently, no correction is introduced.

Within the above framework while this Committee has opted for the above approach to the extrapolation problem, they are aware of the recommendations made by the 22nd ITTC Specialist Committee on Unconventional Propulsors. The latter Committee (ITTC, 1999) recommended that: ship models fitted with unconventional propulsors should be tested as unit and not to be broken down into component tests of the hull and propulsor; furthermore, extrapolation methods of full scale powering should be done using self-propulsion load varying tests of the geometrically similar ship model and propulsor. Although this latter approach appears to be attractive on a number of accounts and worthwhile to pursue in the long term, there has been no application and validation of the procedure for any other well established unconventional propulsors so far. However, there is an encouraging attempt in validating the method for an ice breaker driven by conventional twin screws by (Molloy and Bose, 2001) who have recommended to apply this method to pod driven ships.

6.2 Remarks on the Extrapolation of Propulsion Tests

One of the main purposes of propulsion tests is to determine the wake fraction (w), relative-rotative-efficiency (η_R) and thrust deduction fraction (t) by comparing K_T, K_Q and J obtained from the propulsion tests with K_{Q0} and J_0 from the model-scale open water tests for the same K_T (if K_T identity is used). For podded propulsors, these performance coefficients refer to the pod unit.

In principle, the straightforward application of the ITTC-78 Procedure to podded propulsors implies that the towing force used in the self-propulsion tests should include the skin-friction correction for the hull without any correction for the pod-housing drag. The wake fraction at model-scale is then determined by intersecting the K_T^{unit} value obtained in propulsion tests in the model unit open water test results. The pod-housing drag correction ($F_D^{housing}$) is introduced in this approach as a part of the unit-thrust correction to full-scale for the pod open water characteristics. When this approach is used the unit-thrust loading is that expected at full-scale. However, the propeller is overloaded due to the excessive pod-housing drag present at model-scale. The thrust deduction fraction is then defined in Eq. 6.1.

$$t = \frac{T^{unit-SP} - (R_T - F_D)}{T^{unit-SP}} \quad (6.1)$$

$$t = \frac{T^{unit-SP} + F_D^{housing} - (R_T - F_D)}{T^{unit-SP} + F_D^{housing}} \quad (6.2)$$

Another way of performing the extrapolation is to include, in the towing force, not only the skin friction (F_D) correction but also the above mentioned correction ($F_D^{housing}$). Now the propeller loading is that at full-scale [except for the fact that we are neglecting the friction corrections ΔK_T, ΔK_Q on K_T and K_Q]. In contrast the unit-thrust is too low to be scaled to ship values. So, $F_D^{housing}$ must be added to the measured unit-thrust and such corrected thrust is used to define t in the usual way (Eq. 6.2)

The relative-rotative-efficiency (η_R) for this method can be defined directly from the tests, i.e. η_R is the quotient between the (unit open water) K_Q^{unit-0} and K_Q obtained from the open water and propulsion tests at K_T identity. The wake fraction for the pod unit can be found by intersecting the corrected K_T^{unit} values from the propulsion tests in the corrected open water curves for the same unit (for which $T^{unit-0}_S = T^{unit-0}_M + F_D^{housing}$).

To the Committee's knowledge no investigation has been made to analyse the differences in results predicted from both methods. In principle, both approaches should be equivalent. However, this Committee recommends the second approach in which the towing force includes both F_D and $F_D^{housing}$ corrections. In this way the loading of the model propeller is similar to that at full-scale and the measured torque and rotation rates can be used in the extrapolation to full-scale by direct scaling.

A last remark concerning the entire ITTC-78 Procedure applied to both conventional and podded propulsors is that the prediction of thrust deduction fraction for the full-scale ship can be further refined by adding a friction correction to the thrust resulting from the increase of blade thrust at full-scale Reynolds numbers. Such corrected thrust is to be used to define t in the usual way. This correction is not considered in the present procedure.

6.3 Pod-Housing Drag Scaling

Recently, several methods have been proposed for the extrapolation of pod-housing drag, which are used by leading hydrodynamic testing institutes. These extrapolation methods are described and discussed below.

Method (a). At HSVA, (Mewis and Praefke, 2003) propose to use an approximate calculation of the frictional resistance of the pod-housing. The pod-housing is divided into several zones and the frictional drag is calculated by integrating sectional friction forces strip-wise over each zone, both for full-scale and for model-scale, using simple formulations. The effect of the working propeller is included through the inflow velocity over the zone, which is inside the propeller slipstream, as a function of the propeller thrust loading coefficient. The difference in model- and full-scale frictional resistance values, which are based on respective Reynolds numbers, is taken as the pod-housing scale effect. This method is attractive for its simplicity. However, it overlooks rotation effects in the propeller slipstream for puller- type pods and does not include the scaling of pressure drag, which may be significant for some components of the pod-housing. RANS calculations suggest that the scaling of pressure drag may be in some cases more important than that of the frictional drag. As an example for a particular pod application [Table VII in Sánchez-Caja et al. (2003)] the effect of scaling on a strut expressed as percentages of the model-scale unit-thrust coefficient was -0.4% in frictional resistance and -1.5% in pressure resistance.

Method (b). At MARIN, (Holtrop, 2001) recommends a form-factor based approach where the pod-housing drag is separated into a Reynolds number dependent and Reynolds number independent part. The ratio between the two parts is to be determined for several typical pod brands now on the market, by viscous flow calculations for model- and full-scale, excluding the pod-strut, but including the propeller effect by using an actuator disc model. The difference in model- and full-scale results for the Reynolds number dependent part is translated into a form-factor and that forms the basis for the determination of the pod-housing scale effect. This method also overlooks the rotation in the propeller slipstream and it lacks the effect of the pod-strut on the pod-housing drag. For the pod application considered in the previous paragraph such effect amounts to 1.9% (=1.5+0.4) of the model-scale non-dimensional unit-thrust. For unconventional struts the error due to ignoring the scale effect on the strut may be larger. Additionally, Holtrop's method may lead to form-factor corrections of 3 or 5 times the value corrected, which is indicative of a methodology with vulnerable physics.

Method (c). At SSPA, as reported by Sasaki et al. (2004), the correction on the unit-thrust due to the pod-housing drag is taken into account by comparing the measured pod-housing drag with the calculated one at full-scale. The calculation method is based upon a semi-empirical formula derived for the drag of torpedo shapes. Neither the effect of the working propeller nor that of the strut is included in the semi-empirical formula. The torpedo shapes tested may not be very representative for modern pod-housing shapes and cannot distinguish between several pod types.

Method (d). At Sumitomo, Sasaki et al. (2004) use approximate formulae to calculate the full-scale pod-housing drag in terms of the pod-body, strut and interference components. The effect of propeller induced velocity is represented through inflow velocity and hence Reynolds number for the frictional coefficient of the pod-body and strut parts inside the propeller slipstream. However, the physics behind the empirical formulae for calculating the total resistance coefficient of the pod and the interference effects is not very clear. In particular pods with different aft-ends will have the same resistance coefficient. The method also does not consider the impact of swirling in the slipstream.

Method (e). At KSRI, using RANS based force and flow analysis on two different shapes of puller-type propulsors, Lobachev and Tchitcherine (2001) and Chicherin et al. (2004) indicate that the idea of using a form-factor for the determination of pod-housing drag is not realistic. Instead they suggest another simple method: the full-scale pod-housing drag should be calculated from the pod-housing drag on model-scale from a pod unit open water test and that value should be multiplied by a factor α, which is the resistance ratio of the pod-housing on full-scale divided by the one for model-scale; determined by CFD calculations on the pod-housing for full- and model-scale.

As part of this Committee's activities Sasaki et al. (2004) have investigated the scale correction resulting from each of the above described methods for the single puller-type pod unit of a particular double acting tanker. The results are shown in Fig. 5.5.

In Fig. 6.1 the pod-housing drag scaling factor, $\Delta K_T^{housing}$, is described in Eq. 6.3.

$$\Delta K_T^{housing} = \frac{F_D^{housing}}{\rho n_s^2 D^4} \tag{6.3}$$

where,
ρ is the water density; D is the propeller diameter; n_s is the propeller rate of rotation.

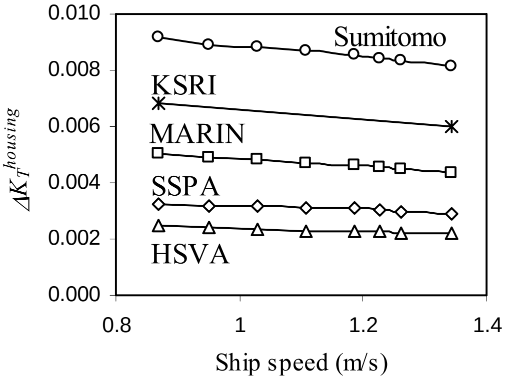

Figure 6.1- Pod-housing drag scaling correction using different methods.

As shown in Fig. 6.1 the paper reports large scatter in the corrections although this does not necessarily imply scatter in the final power prediction. Of the different pod-housing extrapolation methods RANS solver based methods seem to be the most adequate ones available at the moment. Apart from not being tied to the particular know-how of an institution, RANS methods include more sound physics and more accuracy for the representation of the pod-housing geometry than other extrapolation procedures. They also provide information about the forces acting on each component of the pod-housing (strut; pod nacelle; fins), which would be very difficult, if not impossible, to measure in model tests. Generally, the prediction of absolute forces from RANS codes may vary from code to code depending on many factors (turbulence model, type of discretisation in the differential equations). However, the prediction of relative changes in forces when comparing calculations made at different scales are expected to have less scatter due to the fact that computational errors of the same type made at model- and full-scale cancel each other.

6.4 RANS Investigations on Scale Effects

RANS investigations on scale effects have been addressed in Lobachev and Tchitcherine (2001), Sánchez-Caja et al. (2003) and Chicherin et al. (2004). A summary of the papers is given below.

Lobachev and Tchitcherine (2001) present RANS analyses at model- and full-scale for a tractor pod at three advance numbers. The propeller is represented by an actuator disk which produces the thrust and torque levels obtained from model-scale experiments. Numerical scaling is applied to the pod-housing of the unit, not to the propeller non-dimensional force coefficients which are fixed to the model-scale values. A 0.6 million cell grid both for model- and full-scale was used. The turbulence model employed was the *k-epsilon*. Wall functions were used. As the propeller load grows the share of the pressure resistance in the total drag of the pod-housing rises at the expense of the reducing friction resistance component. They found a weak dependence of the $K_{P\&S}$ coefficient on propeller load $K_{P\&S}=-X/(\rho n^2 D^4)$, where X is axial drag of strut and pod, n the rps, and D the propeller diameter. They propose an extrapolation from model-scale values to full-scale based on RANS computations in Eq. 6.4.

$$K_{P\&S}^{ship} = K_{P\&S}^{model} \cdot \frac{K_{P\&S,calc.}^{ship}}{K_{P\&S,calc.}^{model}} \tag{6.4}$$

For the podded propulsor configuration subject to analysis they found that the full-scale resistance is 69% and 63% of the model-scale resistance respectively for the pod-housing with and without the presence of the propeller.

Sanchez-Caja et al. (2003) present a RANS analysis illustrating the complex interaction between the propeller and the passive components in a podded propulsor. Grids of up to 7.5 million cells were built. The *k-epsilon* turbulence model without wall functions was used. A sliding mesh technique was employed for modelling the rotating and stationary parts of the pod unit. Circumferential averaging over a sliding surface was applied in order to reduce the unsteady problem to steady state, and consequently decrease the CPU time. Calculated flow patterns at full-scale are illustrated and compared to those obtained at model-scale. Flow detachment on the nacelle and strut surfaces is shown to be delayed at full-scale. The forces on the different components of the tractor unit are shown and compared to model-scale results.

Large differences are found in the scaling of various passive components of the pod unit. The strut acts like a lifting device for which reduction of trailing edge separation from model- to full-scale means a strong increase of its lifting capability and consequently, noticeable reductions in pressure drag. Other parts are non-lifting bodies that behave also very differently at model- and full-scale depending on their capability to reduce areas of flow separation as the Reynolds number increases. In particular the full-scale resistance ranges between 44 ~ 100% of the model resistance for the different components. The total resistance of the non-rotating components at full-scale is reduced in 14%. The relative contribution of the frictional and pressure forces to the total forces is shown for each component of the pod unit. The percentage of frictional forces to total forces is similar for the different components at full-scale. However, larger differences are found at model-scale.

Chicherin et al. (2004) analyse the two preceding papers and draw some conclusions for the scaling of podded propulsors as follows:

Point (1). Results of RANS-code calculations show that it is inadequate to scale the pod-housing drag with the 0.5 scaling coefficient, which is successfully applied for conventional appendages by some laboratories worldwide. RANS calculations in the open literature suggest that this factor should vary from 0.7 for well-streamlined pod-housings to approximately 0.85~0.86 for blunt ones.

Point (2). The form-factor concept is inapplicable to pod-housing drag scaling because in this case the form-factor is a function of the propeller loading and of the Reynolds number.

Point (3). The most suitable parameter for extrapolation that only weakly depends on the propeller loading is the non-dimensional resistance coefficient used as a correction to the drag of the entire pod unit. The pod-housing thrust coefficient is extrapolated with a scale factor obtained by RANS-code computations at model- and full-scale Reynolds numbers. Depending on the shape of the pod-housing, the scale factor is within 0.70 ~ 0.86. The lower value belongs to streamlined designs whereas the higher one represents pod-housings that stimulate extensive flow separation.

6.5 Final Remarks

The most important difficulty encountered by this Committee for defining a suitable extrapolation procedure for podded propulsors has been the lack of full-scale data; not a single case has been published. The Committee makes a call for collaborative work, which can be formulated as follows.

For a known target vessel equipped with standard podded propulsors, full-scale trial results should be made available from a pod manufacturer, ship owner or other sources. The podded propulsor details should be distributed to participating testing institutes. These institutes can perform model tests with the similar size models. The differences between the model test results can reveal the effect of different instrumentation. This may turn out to be impractical and since the unit open water tests are the most critical ones, perhaps only this group of tests can be performed at the participating institutes. Even if this is not feasible, only one institute can perform the tests and provide the raw data to the collaborating group. Of course these data will have the uncertainty of having been carried out in one institute. Then, extrapolation will be carried out using appropriate corrections (including different approaches) and the results will be compared to the full-scale data.

Even the above proposed approach will have an associated uncertainty since it only refers to a single ship. But we can learn a lot from such an exercise and provide a reference for building a useful database for future studies and other proposals for extrapolation such as by ITTC (1999) and Molloy and Bose (2001).

Finally, with no data available, this Committee suggests that the procedure proposed in Appendix A be used with the different housing-drag corrections, as well as clearly documenting the corrections. Also, this Committee recommends utilizing RANS based prediction methods for the pod-housing drag correction as these represent the physics of the phenomenon.

7. PROCEDURES FOR MODEL-SCALE CAVITATION EXPERIMENTS

7.1 Approach for Procedures

Although many testing facilities have been conducting model tests with podded propulsors there is hardly any direct study, reported in the open literature, to describe procedures for the conduct of model-scale cavitation tests. In the absence of such specific knowledge, an appropriate starting point is the existing procedures for conventional propellers.

To accomplish this task, the Committee therefore adopts an approach of a similar format to that used in the Recommended Procedures for Model-Scale Cavitation Tests for the conventional propeller, (ITTC, 2002a). However, emphasis is made wherever necessary with regard to different features of podded propulsors. An additional section is also included in the new procedures under the heading of “Description of Cavitation Appearances”; while this aspect is a separate chapter in the recommended procedure for conventional propeller.

In the following sections the new procedures recommended by this Committee, (ITTC, 2005), are briefly reviewed with specific emphasis on their main features.

7.2 Review of the Procedures

General Issues. The main objective of the procedures is to provide a common base to carry out model-scale cavitation tests with podded propulsors to give results which are consistent, reliable and comparable.

Herein, a podded propulsor, as described in Section 5.3, is a whole *unit* including its propeller(s), lower part of the pod (housing the motor), upper part of the pod (strut), fin, flap and duct. Within this framework the emphasis is made that the test should be conducted with strictly scaled, complete pod units with or without a hull model or a dummy hull model. The size of the podded propulsor model should be such that the highest possible Reynolds number is achieved within an acceptable level of test-section-blockage and within the capacity constraint of the test facility. Tolerances for the propeller blade surfaces and other stationary parts of the propulsion unit are expected to be similar and the entire unit must have high rigidity and geometric accuracy.

Basic calibrations of pressure gauges, torque dynamometer, corrections for the torque for the bare hub, establishment of instrument zeros taking account of friction, checks for vibration levels of the propulsion unit and shaft balancing have to be performed as usual. Also, water quality issues, including some knowledge of the nuclei size and distribution, liquid tension as well as dissolved gas content, should be provided as recommended for the conventional propeller cavitation tests, particularly during cavitation inception tests.

Propulsion Unit Operating Conditions. One of the important aspects of the cavitation test is the establishment of the podded propulsor operating conditions and correct simulation of these conditions in the testing facility.

The operating conditions should be mutually established between the testing organisation and the customer. Having established these conditions, the detailed test parameters, required to set the cavitation test conditions, are taken from the results of self-propulsion model tests, scaled to the ship self-propulsion point. These parameters are cavitation number σ, advance coefficient J_A, and ideally, the full-scale propeller thrust coefficient K_T. Then, at a particular operating point, the tunnel flow condition is set on the basis of “thrust identity”. However, considering the current uncertainty in accurate measurement of thrust on the propeller of a podded propulsor due to the propeller gap effect, the Committee recommends running the cavitation test at a “torque identity” condition satisfying a target full-scale torque coefficient K_Q, value of the podded propulsor.

The Committee notes that some testing organisations opt for the use of full-scale unit-thrust coefficient $K_T^{\ unit}$, based on the thrust identity as an alternative to using the full-scale propeller thrust coefficient K_T. Unfortunately, this will result in incorrect propeller loading and thus is not recommended by this Committee.

Once the decision is made on the test parameters, the choice of propeller rpm and tunnel speed, within the capability of the testing facility should result in sufficiently high blade Reynolds number, particularly for puller-type podded propulsors.

For some of the operating conditions, it may be required to conduct tests at varying azimuth and tilt angles. This is usually required to optimise the orientation of the podded propulsor as well as to observe cavitation patterns in off-design conditions. While such tests are valid for small helm angles, it can be questionable at larger angles since the inflow will be modified by yawing motion; hence not the correct wake flow.

By testing the pod at varying static and, if possible, dynamic helm angles, invaluable information on performance in the off-design condition and on complex flow behaviour can be obtained, (Heinke, 2004) and (Friesch, 2004).

Wake Simulation. The wake simulation adopted for the test should be mutually established between the testing organization and the customer, and should be documented with wake survey procedures or verified to be similar to previously measured configurations.

For pusher-type pods the wake will show strong velocity deficit contours in the top sector of the propeller plane; in general, stronger than for conventional single screw ships. This will be further complicated by strong variations in the transverse and radial velocity component distributions adversely affecting propeller cavitation. This implies that the scale effects in the model wake will play an important rôle in the simulation of the full-scale wake and thus much attention should be paid to create sufficiently high turbulence of the flow over the pod-housing. In these circumstances it is recommended to test at the highest Reynolds number possible and use means to stimulate turbulence (artificial roughening of the pod-housing).

The puller-type pod is less complicated. This is because the propeller operates in a more or less uniform flow with only small effects of the hull boundary layer at the top sector of the propeller plane and with a certain blockage effect of the pod-housing behind the propeller. The presence of the pod-housing behind the propeller is therefore believed to be sufficient for a good simulation of the blockage of the full-scale propeller. It is also believed that the magnitude of the scale effects associated with the pod-housing is smaller compared to the pusher-type pod due to increased turbulence caused by the propeller flow.

In order to aid the propeller designer and for calculation of the propeller cavitation characteristics it is necessary to incorporate the deceleration in the wake field in front of the pod housing for a puller-type podded propulsor. This effect, which was demonstrated by Wang et al. (2004), is simulated automatically due to the presence of the pod housing in cavitation tests.

For the simulation of the hull, the recommended procedures for conventional drives with several options apply: parallel plate/variable density screen wake generators; foreshortened/full length complete hull models. In cases where the propeller is outside the hull boundary layer, the presence of the properly scaled pod-housing with proper alignment relative to the flow should be sufficient to achieve a good wake simulation. If part of the propeller operates in the hull boundary layer, this will require one of the above mentioned options to simulate the model-scale hull wake properly, in addition to other requirements.

Podded Propulsor Model Marking. Suitable marking is required on the pod-body for accurate interpretation of the location and extent of cavitation patterns. Following the similar procedures propeller blades, hub and bossing are marked as recommended for a conventional propeller. The pod-body recommended marking procedure is given in Fig. 7.1.

Cavitation Observations. The whole podded propulsor, including the suction side (*SS*) and the pressure side (*PS*) of the propeller blades, as well as other components of the podded propulsor, must be viewed if required at a prescribed range of helm and flap angles. Standard options for the mode of observations are similar to the options for conventional propeller tests.

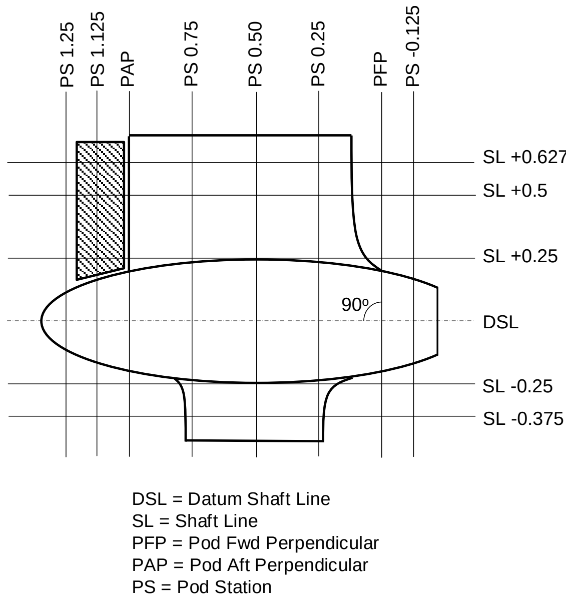

Figure 7.1- Pod-body grid definition.

Cavitation Inception Test. Since a podded propulsor consists of propeller and other components, the inception of cavitation on the prominent locations of these components (strut leading edge; fore and tail end of pod body; flap; fin tips) will be of interest in addition to the inception of cavitation on the propeller blades.

While the practice of testing, recording, scaling and construction of inception diagrams is similar to that for the conventional propeller (plotting of observed cavitation points in a diagram of cavitation number σ, versus advance coefficient J, for the latter) it will be of interest to repeat the inception diagram for several prescribed pod helm angles δ, and/or flap angles if any movable flap exists.

Reporting Cavitation Patterns. It is recommended that adequate reporting of model cavitation patterns on the propeller and other components of the podded propulsor should be made using display of still photographs or sketches as well as video presentations. The latter are particularly useful to display any special cavitation regions and the nature of the cavitation pattern as well as to discuss and interpret the type and range of these patterns in reporting.

Special attention should be paid to the suction and pressure side cavitation for all pertinent blade positions, helm and flap angles. Similar attention should be paid to the cavitation developed on other components by taking into account the flow asymmetry introduced by the effect of helm/flap angles. It is also necessary to make notes on the character and unsteadiness of the observed cavitation patterns in the reporting stage.

Description of Cavitation Appearances. Similar to the case for conventional propellers, the description of cavitation appearances should contain information on: cavitation type; cavity location; size; structure; dynamics; and reference to the prevailing flow dynamics. Descriptive terms, used to identify the various types of cavitation observed during tests, are shown in Fig. 7.2 for a high speed puller-type pod; which is equipped with bottom fin and tail flap, and set at a helm angle.

By considering its propeller and pod-body, cavity location should be specified. For the propeller cavitation, reference should be made to its radial, chord-wise, suction and pressure side location as well as the location in wake. For the pod-body cavity location reference should be made as described by Fig. 7.1. Cavity size should be determined in terms of appropriate body dimensions of the respective component of the podded propulsor (fraction of the propeller blade area; fraction of the projected area of the strut; pod; fin; flap).

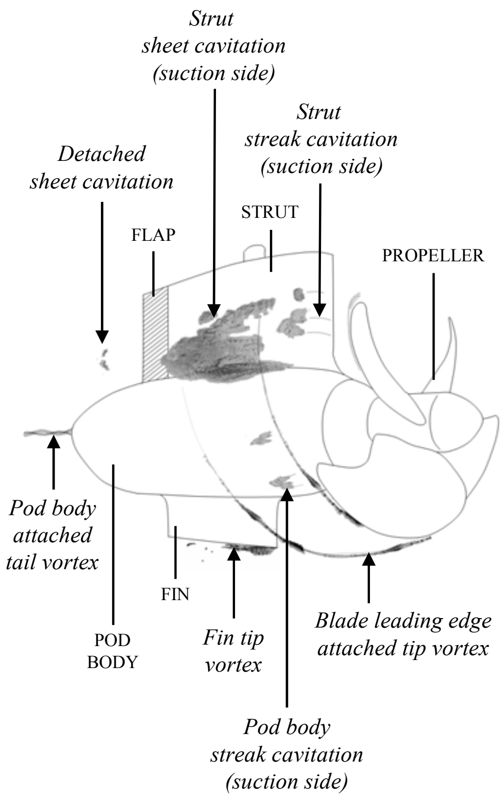

Figure 7.2- Some cavitation type definitions for a puller-type podded propulsor.

The following should be stated in the report as completely as possible:

- description of prominent types of cavitation (vortex; sheet; bubble),
- categorization of cavity dynamics (steady; unsteady; periodic),
- flow regime associated with certain cavitation types (laminar/turbulent boundary layer; steady unsteady/unsteady flow; separated; ventilated).

7.3 Review of Literature

In discussing various hydrodynamic aspects of podded propulsion, based on cavitation tunnel tests, Friesch (2001 and 2004) places emphasis on the use of whole ship models in cavitation tests using large facilities. It is claimed that the use of the same self-propulsion model and pod units in cavitation tests will help to meet the absolute necessity of accurate simulation of the wake and the hull geometry and bring the reproducibility of the test data within range of 1~1.5%. Emphasis is also placed on the measurements of the propeller thrust, torque and revolution pick-ups directly at the shaft while those of the unit-thrust and side-force using a force balance mounted water tight in the ship model. The fitting of pod unit(s) to an adjustable frame is preferred to test the model at different helm angles (even dynamically controlled) and tilt angles so that optimum orientations can be found not only from the propulsion point of view but also in consideration of the cavitation behaviour of the propeller and pod-housing. Large rotational speeds (up to 35 r/s) and model propeller diameters (210~260mm) are recommended to reach high Reynolds numbers comparable with those for conventional propeller shaft arrangements.

In another study Szantyr (2001a) presents hydrodynamic model experiments with a generic podded propulsor to provide insight into the characteristic physical phenomenon associated with operation of podded propulsors. The experiments were conducted in a cavitation tunnel and observation of cavitation undertaken with a symmetric pod unit in the pushing, pulling and combined (tandem propeller; each fitted at one end of the pod) modes for different steering angles. The emphasis is placed on the interaction between the pod-housing and the cavitation tip vortex system of the propeller(s).

In a recent investigation, Heinke (2004) reports on systematic model tests, some of which were carried out in a large circulating and cavitation tunnel, with a 4- and 5-bladed propeller in pull- and push-mode fitted to a generic pod-housing. Using a new z-drive dynamometer and a six component balance he presents systematic data for forces and moments on the propeller and pod body at different steering angles including the effect of cavitation at conditions for blocked propeller, low number of revolutions (simulating crash stop) and at the design speed and revolutions with dynamically turning pod. The latter case, which may represent an unrealistic operating condition at large steering angles, presents a strong flow separation and cavitation leading to a reduction of propeller torque and thrust.

Investigation reported by Wang et al. (2004) involves measurements of velocity fields around the pod unit fitted to a shortened hull model and in the propeller wake flow using LDA in a medium size cavitation tunnel. The interesting feature of this study is the use of a shortened body and axial wake screens to simulate the hull boundary layer of a relatively high speed Ropax hull to demonstrate the strong interaction between the hull and pod unit flow which reflects in the nominal wake field at the propeller plane. Based upon the analysis of the wake measurements with and without the pod unit, the mean wake fraction values are found to be 0.124 and 0.078, respectively, indicating the strong effect of pod-housing. The study hence emphasises the importance and necessity of the 3-D presence of the pod unit for correct wake simulations in small to medium size cavitation tunnels.

7.4 Concluding Remarks

The committee recommends a new set of procedures for model-scale cavitation tests for podded propulsors based upon the procedures for conventional propellers but making appropriate amendments for the special features of these propulsors.

These features imply the consideration of a podded propulsor as a whole unit (propeller(s); housing; fins; flaps; duct) to simulate its hydrodynamic presence as precisely as possible. An accurate simulation of the hull wake, depending upon the pull- or push-mode, requires particular attention. Reporting of cavitation patterns and inception data can be important not only for its propeller but also for other components of the podded propulsor by considering integrated nature of these propulsors.

By taking into account current uncertainty regarding the accurate measurement of the propeller thrust the Committee, for the time being, recommends the use of the full-scale torque coefficient through the torque identity method in setting cavitation test conditions.

By considering the integrated function of these propulsors, as reported in open literature, there is a tendency to perform model-scale cavitation tests with pod units at varying static and dynamically controlled helm angles using sophisticated dynamometers and balance mechanisms.

The Committee, particularly, recognizes the potential importance of dynamically controlled cavitation tests since they can provide valuable insight into some complex flow and cavitation phenomenon, which will occur during full-scale operations. However the development of appropriate procedures for such tests and the accuracy of their implications will require further investigations.

8. IMPACT OF OFF-DESIGN CONDITIONS ON LOADS AND STABILITY

8.1 Off-Design Conditions

In contrast to conventional propeller systems with rudders, podded propulsors 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 be result in structural failure as well as in motion instability due to large induced initial heel and roll angles. Therefore the consideration of the off-design conditions is crucial in the design of pods and their propellers, as well as in the prediction of propulsive and manoeuvring characteristics of ships driven by these propulsion devices.

8.2 Classification of Off-Design Conditions

Pustoshny and Kaprantsev (2001) conducted full-scale cavitation observations on the azimuthing podded propulsors of *Elation*, the first passenger ship equipped with electric azimuthing podded propulsors, and suggested the following operation modes as the key off-design conditions for these devices.

Acceleration. All processes associated with this mode are the same as for conventional shaft-mounted propellers. Initially, there are high hydrodynamic loads on the propeller blades and the highest probability of tip vortex cavitation with a tendency to approach the design-mode cavitation pattern as the ship speed rises towards the design value. Some propeller manufacturers consider the bollard-pull-ahead scenario as the most dangerous situation for the propeller strength, and this is indeed a good approximation for the most dangerous phase of the acceleration mode.

Normal Steering. As a rule, normal steering for a ship with podded propulsors involves helm (steering) angles within ±7~10^{o} around the straight-ahead condition. Such magnitudes are normal for twin-screw ships and pose no danger for the blade strength or cavitation, either for the propeller or for the strut. Moreover, incidence angles of the strut associated with these steering angles are even less than those of conventional rudders. The propeller of a pod turns together with the entire pod structure when it is slewed, and therefore the axial component of the induced velocity in the propeller slipstream is directed along the strut. If only a lower fin or flap is present, cavitation risks due to the effect of tip vortex on a short foil may increase. In fact, the fin connected to the pod may be considered together as a short foil installed with an incidence angle. The importance of such tip vortices was revealed in model tests with podded propulsors (especially with pusher-types) where the propeller and unit hydrodynamic characteristics versus steering angles were asymmetric relative to the zero angle due to the impact of the tip vortex.

Extreme Steering. This is the mode when the podded propulsor is slewed through angles exceeding 7~10^o, which in practical terms means a range of 15~30^o. As follows from Kurimo (1998) and Pustoshny and Kaprantsev (2001), in this case, the ship enters into a turning circle, the speed drops and the propeller advance ratio decreases. There is 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 (side) loads on the entire pod unit due to their high acceleration dependency. Woodward et al. (2005b) present model test results showing spike loads experienced at the pods for two different ships and show that these side loads can be modelled reasonably well. The magnitude of the spike loads is shown to be acceleration dependent and 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. They suggest that, ensuring the initial design has positive course stability helps to reduce the magnitude of spike loading and induced roll effects. They also concluded that, the sensitivity to slew rate is smaller, however this is easy to vary and should be kept as low as is practical. The most significant component dictating the control force generated by the pod is the strut; acting as a lifting surface.

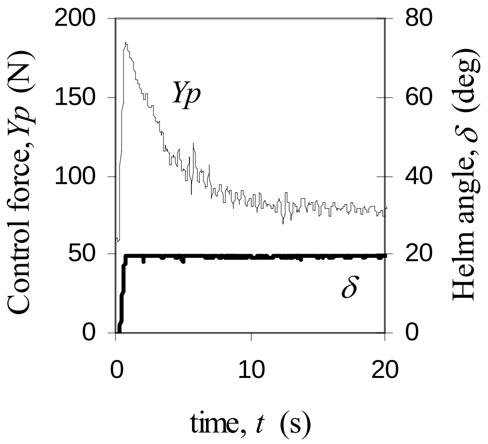

Figure 8.1- Side force measured on podded model.

Woodward et al. (2005b) present turning circle model test results clearly demonstrating a side force of more than double that of the steady state when slewing the pod, as shown in Fig. 8.1. Though these loads do not impact directly on the manoeuvring response they have significant implications for the structural design of the pod and its seating at the aft end of the vessel and may also induce considerable roll.

Figure 8.2 illustrates the latter effect recorded during the turning manoeuvre test of a large Ropax model driven by four puller type pods, two azimuthing pods at the back and two fixed pods in front, (Woodward et al., 2005b). While an acceptable list angle can be observed during the steady turning, a large initial rolling angle is very clear at the start of the turning manoeuvre.

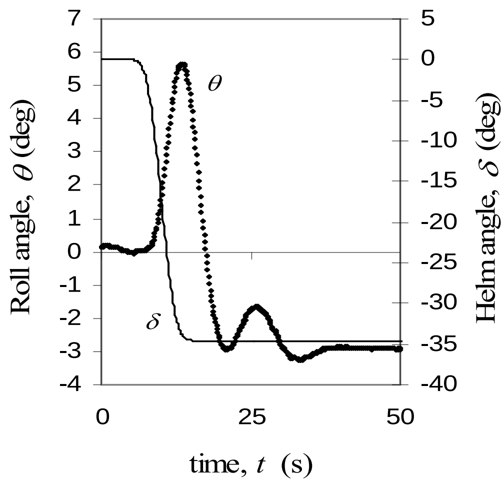

Figure 8.2- Turn initiated roll recorded on a pod driven model.

Within the same context Toxopeus and Loeff (2002) investigated the merits and drawbacks of the manoeuvring characteristics related to the application of podded propulsors. They draw attention to the heel/roll behaviour while manoeuvring with the pod-driven ship; although the turning ability itself was not a problem when judging the applicability of podded propulsors. These behaviours are attributed to high turning rates which induce large gyration forces and thus large roll motions. The resulting roll angles in turn can affect the turning rate and the course stability. Based upon their database they demonstrated 28^o maximum roll and 17^o constant heel at high speed and large steering angles. They claim that maximum roll angle greater than 13^o and constant heel angle larger than 8^o are cause for concern and these are not covered by the current IMO criteria.

The steering related heel/roll behaviour has also been the subject of investigation by others. Amongst them Lepeix (2001) draws attention to the possibility of unacceptable heel angles to be associated with reduced tactical diameters with the podded propulsor driven ships.

Hamalainen and van Heerd (2001) suggest 4^o of maximum heel angle restriction for large cruise vessels during manoeuvring. Van Terwisga et al. (2001) also suggest a similar restriction based on the 7^o panic limit for passengers and indicates the necessity for suitable design modifications to hull-forms to ensure that the subject heel angles should remain in acceptable limits.

Crash Stop. This is the mode experienced in an emergency situation and it involves both ship's hull and the podded propulsor. 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. In the following, various modes of crash stop manoeuvres, which can be conducted with podded propulsors, reported in the open literature are described.

Crash Stop by Changing the Direction of Propeller Rotation: 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 the time with a conventional (mechanical) drive system. Thus, the propeller starts running full-astern while the ship still has a significant forward speed. This means that, for a podded propulsor, the propeller strength issue under the crash-stop mode is even more vital than ahead or astern bollard-pull conditions. 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 would entail high vibrations and noise radiation.

Crash Stop by Turning the Podded Propulsor Around: 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 crash stopping by changing the propeller rotation direction.

Bushkovsky et al. (2003b) investigated various aspects of the crash stop by podded propulsor turning. The key problem of this scenario is the blade loading. It should be borne in mind that it is important not only when the propeller is in oblique condition due to helm effect (it was found that the most dangerous helm angles are about 60~70^o from the ship speed vector), but also important when the propeller operates opposite to the ship speed at the final stage of the crash-stop manoeuvre. However, in the latter case the propeller operates with the 'correct' rotation direction since its leading edges face forward (unlike when making the crash stop by reversing the propeller rotation). This is more dangerous for the strength point of view; especially for a high-skew propeller.

Crash Stop by Indirect Manoeuvre: Again, this mode of stopping is not applicable to single pod applications. However, for twin pod ships, it is possible to turn the pods to opposite helm angles and thereto use the induced lift as a braking force; as described by Woodward et al. (2004).

A numerical simulation used to make comparison of four stopping manoeuvres, is given by Woodward et al. (2004 and 2005a) including: (1) changing the direction of propeller rotation (reversing the thrust); (2) turning the pods around; (3) turning the pods around while reducing the thrust; (4) turning the pods to 60^o in opposite directions while reversing the thrust called “Indirect Manoeuvre”. The results of this analysis demonstrate that reversing the thrust (1) provides a low, continuous load on the pod, resulting in the longest stopping time and distance. The analysis does not however consider the poorly distributed and unsteady forces experienced by the propeller. Comparison of stopping by turning the pods around (2) demonstrates that far greater forces can be generated by the pod system than can be generated by the propeller alone. The results show that a reduction in MCR, while extending the stopping distance, does not significantly reduce the peak forces on the pod. This is considered to be due to the propeller/shaft/motor mass inertia, initially sustaining an rpm value not possible with the motor torque alone. Clearly, it is possible that this inertia-sustained rpm could induce high propeller stresses. The indirect manoeuvre case (4) demonstrates the shortest stopping time and distance. The results show a more sustained braking force but with significantly lower peak loads than when turning the pods around. A further advantage of the indirect manoeuvre is quoted to be that induced asymmetry between pod helm angles can provide large steering forces; resulting in a safer, faster and far more controlled stopping operation. The proposed model does not take into account the effect of interaction between pods nor cavitation which can be apparent, particularly at increasing helm angles.

Crabbing and Dynamic Positioning. Crabbing and dynamic positioning are even more traditional operation modes for thrusters and podded propulsor than their main-propulsion function. The idea that the thrusters should combine the rôles of main propulsion and Dynamic Positioning (DP), came up in design investigations during the 1980s in connection with rapidly developing mine hunters and deepwater diving support vessels. There were several investigations formulating the involved requirements of high efficiency in the propulsion (design) mode, and the thrust and noise levels in the DP mode or other scenarios which are close to bollard-pull conditions (e.g. Bjarne, 1982, Daniel, 1984, Pitts and Dorey, 1984, Pustoshny and Semionicheva, 1996).

The problem of how the propeller design could satisfy both the speed and the bollard-pull specifications initially motivated developing Voith-Schneider Propellers (VSP) as main propulsors. Nevertheless, after some time, azimuthing 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 and open propellers: Ducted propellers offer up to 30% advantages in thrust and cavitation free bollard pull thrust but they are slightly less efficient under design-speed conditions as well as being more sensitive to oblique flows; and
- Blades with or without tip unloading: Tip unloading improves cavitation characteristics under both design-speed and bollard-pull conditions at high propeller loads but reduces the bollard-pull thrust and may be disadvantageous for lightly-loaded CPPs in the DP mode (Pustoshny et al., 1996)

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 best solution is to conduct model tests in a depressurised tank. Fortunately, the real situation is easier because cavitation effects under bollard-pull conditions and with small J values are usually very much similar: the tip vortex cavitation was registered in numerous model tests and full-scale trials (Kaprantsev et al., 2000). This may be additionally confirmed by the behaviour of the left branch of the cavitation bucket near the bollard-pull point, which is nearly parallel with the *J*-axis.

Special attention should be paid to the crabbing mode when the ship moves with a low speed but the podded propulsor 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.

8.3 Review of Research on the Off-Design Conditions

Experimental Investigations. Szantyr (2001a and 2001b) published one of the first sets of systematic experimental data on podded propulsors in the main propulsion rôle with oblique incidence angles. This experimental programme covered cavitation tunnel tests with a twin-screw (tandem) pod, whose propellers were fitted at the fore and the aft ends of the pod as well as with a puller- and pusher-type pods. The thrusters were tested at zero and $\pm 15^o$ drift or steering angles. Comparing the hydrodynamic characteristics of the puller-type and twin-screw thrusters, Szantyr concluded that the drift angle had a pronounced effect upon the axial hydrodynamic force on the twin-screw podded drive and a similar though smaller effect upon the system with a single puller-type propeller. The propeller rotation direction had some effect on variations of the axial hydrodynamic force with the drift angle: the force increase was greater with turns coinciding with the propeller rotation direction. Transverse hydrodynamic force variations with the drift angle also depended on the propeller rotation direction. Generally, as has been mentioned above, hydrodynamic characteristics of the podded drive are found to be asymmetric with respect to the drift angle.

He has also investigated the cavitation aspect of the propeller under speed-ahead and steering conditions. He 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 rather small.

Grygorowicz and Szantyr (2004) reported open-water tests of puller- and pusher-type pods in a rotating-arm basin. A complete pod was mounted on a 6-component strain-gauge dynamometer and measurements were made of the resulting forces and moments in a range of advance ratios combined with a range of drift angles from $\pm 30^o$ for puller- and pusher-type thrusters. Also, measurements were made with the pod without the propellers. The test programme also included the same drift angles with the reversed propeller rotation direction.

The published detailed plots are very useful for practical applications. With both tested propulsion options, lateral forces and vertical moments were complex functions of the propeller loading and of the external flow velocity. It was important which flow velocity/propeller speed combination served to control the advance ratio.

Woodward et al. (2004) present results of a double pod set when captive tested in a towing tank at various helm angles and advance coefficients. 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.

Heinke (2004) has published experimental results on forces and moments on a pod and its propeller both measured at steady (fixed) steering angles and at dynamic condition while turning the pod. He obtained detailed 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. He claimed that forces and moments observed in the dynamic conditions were slightly higher than those obtained in tests at fixed angles.

The results reported by Heinke (2004) open a new avenue in experimental investigation; including dynamic tests with rotating pods. Obviously, in such tests, one should carefully consider the similarity parameters like the ratio between the propeller revolutions and steering rates. Nevertheless, those tests were a significant step in experimental hydrodynamics of podded propulsors. On the other hand, the obtained results demonstrate that the pseudo-steady approach is quite acceptable for predicting forces and moments on propellers and podded drive systems.

Stettler et al. (2004) also investigated the dynamics of podded propulsor forces in relation to manoeuvring estimations. They tested the pod model in the towing tank of the Massachusetts Institute of Technology (MIT). In spite of the fact that the facility was able to measure both pseudo-steady and dynamic forces on the unit, the report offered only pseudo-steady results for a broad range of steering angles and advance ratios. Those results were a set of pseudo-steady functions for the thrust, the normal force, the torque and the steering moment. Unique PIV images of wake velocity fields and vorticity distributions behind the propeller in oblique flows under pseudo-steady and dynamic conditions are presented. The difference in vortex wake pitches on the two sides of the propeller was investigated and the behaviour of the starting ring vortex was also registered. Very valuable information for the estimation of forces is available in the demonstration of dynamic variations of the forces. Obviously, it is very important to consider not only the growth of the mean force, but also its fluctuations with amplitudes that are quite comparable with the averaged value (up to 50%).

Moukhina and Yakovlev (2001) also investigated propeller hydrodynamic forces associated with ship manoeuvring. They have developed a computation method for forces and moments arising on the propeller at high oblique flow angles. Up to 90^o, the procedure applies the vortex theory and accounts for the swirling and the curvature of the propeller slipstream. For higher (90~180^o) angles and near the bollard-pull scenario, they use a simplified model based on vortex-theory calculations and experimental corrections to blade section characteristics at high incidence angles.

<u>CFD Based Investigations.</u> Though the last decade has seen various CFD tools, including potential boundary element (or panel) methods, RANS or hybrid potential-flow/RANS methods, applied to performance predictions for podded propulsors under straight-course and, to a lesser extent, manoeuvring conditions, open publications can offer only very few examples of CFD computations for podded propulsors under off-design conditions. Junglewitz et al. (2004a) presented calculations for steering forces and moments using an unsteady RANS code. Based on those calculations, they concluded that design-speed steering capabilities of podded propulsors should not be much superior to conventional rudders. However, steering with the pods at lower speeds was definitely advantageous. Fractions of the side force for different components of the pod were discussed based on the RANS solution.

There are no publications on crash-ahead and crash-back manoeuvres dedicated exclusively to podded propulsors, and the available papers deal with conventional open propellers only. Cheng and Stern (1998) presented four-quadrant flow unsteady RANS calculations using the Baldwin-Lomax turbulence model. They got a close agreement of predicted performances for the forward and backing conditions with experimental results whereas for the crash-ahead and crash-back scenarios, the agreement was only qualitative. The predicted ring vortex for the crash-back condition was in a qualitative agreement with the experimental data.

Junglewitz et al. (2004b) have applied a RANS code and the ANSYS FEM software for estimating flow characteristics and forces on SSP 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, in a recent paper, Jessup et al. (2004) 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 (Kurimo et al., 1997) that considered the crash stop as the crucial point in the podded propulsor strength analysis because of the very quick and powerful crash-stopping, typical of electric podded driven systems.

8.4 Concluding Remarks

The above review demonstrates that the major challenges of podded propulsors 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 advisable to apply mostly the CFD procedures. Model experiments serve today for pseudo-steady investigations into integral forces (on podded propulsors in oblique flows). However, latest publications indicate a rapid progress in dynamometers suitable for dynamic testing.

Investigations into the dynamic process of a turning podded propulsor 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 podded propulsors in steering and manoeuvring modes;
- Reviewing and updating procedures for podded propulsor cavitation model tests under off-design conditions.

In the meantime, dedicated simulation studies supported by the limited amount of model tests identify that podded propulsors 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.

9. IMPACT ON THE IMO MANOEUVRING CRITERIA

9.1 Definition of the Problem

At a first glance, it could be easy to conclude that an azimuthing podded propulsor is simply an integrated propulsion unit wholly replacing the actions of a separate propeller and rudder. After all, the strut and pod-housing are very similar to a rudder and a puller-type propeller arrangement will accelerate the flow over this ‘rudder’ very much as with a conventional arrangement. This is however, about where the similarities end. Unlike a conventional rudder, the accelerated flow from the propeller race stays, for the most part, parallel to the pod when slewed. Also, the propeller must accept an asymmetric inflow as it is placed at an angle of attack; producing forces very different to those in the straight-ahead condition.

As far as the manoeuvring responses are concerned the podded propulsor is not the only contributing factor with respect to the response of the subject ship. In fact, the shape of the ship's hull plays a pivotal rôle in the manoeuvring characteristics of the total system. In practice, the introduction of podded propulsors requires a significant modification to the stern region of the ship's hull. To make room for the azimuthing capabilities, the hull must become more 'prammed' and consequently broader at the stern. The aft-body water-plane area increases; moving the position of the longitudinal centre of flotation (LCF) toward the stern of the ship. Also, a reduction in the aft-body volume is often unavoidable and, for constant displacement, the resulting increase in forward body volume moves the longitudinal centre of buoyancy (LCB) forward. Accompanying the hydrodynamic influences of such a modification, the change in LCB necessitates a change in the longitudinal centre of mass which further influences the dynamic behaviour of the ship.

The central skeg or deadwood, characteristic of a hull-form designed for a conventional propulsion arrangement acts in many ways like the tail fin on an aircraft. This fin-like structure, situated deep and well to the stern of the ship, serves as a stabilising influence on the overall system. On the other hand, the more 'prammed' stern-form, characteristic of a hull-form designed for a pod-driven ship has no tail fin so to speak. Similar 'pram like' stern forms have been used with in the past for various reasons; including some promising resistance characteristics. However, failure to consider the effects on direction course stability at the design stage has resulted in some unpleasant surprises. If other characteristics of the ship tend toward a less than stable form then, pramming the stern can result in a ship with such severe tendencies that it is impossible to control neither by man nor machine. In some cases, the retrofitting of large rudder like fins on the aft quarters has been required to rescue the design.

Neglecting the effect on manoeuvring behaviour caused by changes in the stern-form can have serious and costly repercussions. The re-emergence of the pram stern, used for pod-driven ships, therefore has warranted close attention in recent investigations.

9.2 Critical Review of IMO Manoeuvring Criteria Regarding Pod-Driven Ships

In a recent research study Woodward (2005) looks into the individual IMO Standard Manoeuvres and makes critical analysis of their application to pod-driven ships. Based on this study, the following text describes in brief and makes critical assessment of, the requirements for ship manoeuvring performance, defined through the use of specific criteria as specified by the International Maritime Organisation – Interim standards for ship manoeuvrability; for full text readers are referred to (IMO, 2002). The standards should be applied to all ships of all rudder and propulsion types, of 100 meters in length and over, and chemical tankers and gas carriers regardless of length. The standard manoeuvres should be performed without the use of any manoeuvring aids which are not continuously and readily available in normal operation.

Turning Circle Criterion. Current literature would indicate that the turning circle parameters are easily obtainable with existing pod-driven ships. In fact, Kurimo (1998) suggests that the traditionally defined parameters become so small that a more relevant description of the resulting turn could be based on a sweep-area. However, there is really no question of the applicability of the advance and tactical diameter requirements. After all, these limits clearly define a benchmark operational envelope irrespective of how the control force is applied. What is perhaps less clear is the specific application of helm angle for a podded propulsor. A conventional rudder will provide a control force up to an angle of attack beyond which flow separation occurs. The application of the 35^o helm angle for the turning manoeuvre assumes that the maximum control force available is when the helm is hard across. However, a podded propulsor can be rotated to any angle creating a greater or lesser degree of control force; 35^o therefore has little meaning when you have 360^o to choose from. In fact, the complex hydrodynamic interaction between the propeller and the pod-body would suggest that the control force is a function of many parameters including ship speed, yaw rate, propeller rpm and the helm angle. For the pilot of a pod-driven ship it is not immediately clear what helm angle would produce either the most efficient manoeuvre or the fastest response in an emergency.

Initial Turning Criterion. This manoeuvre is essentially a measure of the transient state response to a specific helm input. A certain level of directional course-stability is necessary for the safe and practical operation of a ship however; excessive course stability or 'super stability' will result in a ship that is difficult to turn. The initial turning test is also significantly influenced by the time-domain response of the steering gear. The mass of a podded propulsor, in general, is about six times larger than the corresponding rudder – making the slewing acceleration far more influential. Also, as with the turning manoeuvre, the definition of helm angle is less clear. The 10^o rudder specification amounts to about 25~30% of the total available control force. Again, it is not entirely clear if a 10^o applied helm angle amounts to a greater or lesser proportion of the available control force afforded by a podded propulsor.

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

Stopping Criterion. While it is still perfectly satisfactory to reverse the shaft rotation on a podded propulsor, we are now presented with other options for stopping that may be more effective or less demanding on the propeller. Clearly, the first variation would be to turn the pod around without reducing rpm. While running the propeller in a highly overloaded condition it would at least be operating in the correct sense of rotation. Boushkovsky et al. (2003b) report that this manoeuvre may cause dangerously high blade stresses and claims that a 60% reduction in MCR can ensure safe propeller operation. A further option would be to imitate the tug operation known as 'the indirect mode' described by Smith (2002). For example, both pods can be turned in opposite directions to say, 30^o helm, using the generated lift as a braking force; described by Woodward et al. (2004). Finally, a stopping manoeuvre involving a tight turn could be implemented, as described by Kurimo

(1998), which would stop the ship with far less head reach but much increased deviation.

9.3 Ability to Satisfy the Criteria

The following text 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 hydrodynamic 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*), at that time, 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 conventionally propelled vessels presented some minor improvement in favour of the latter. The paper notes that, the classification society and SOLAS requirements treat the pod as azimuthing thrusters and hence apply 9^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, 1999) 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 ships 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. (2002a) present a comparative study of the manoeuvring performance when using both conventional propulsion and podded propulsors 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 Byström (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, as already mentioned in Section 8.2 within the framework of off-design conditions, 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 podded propulsors.

Finally, as already reviewed in Section 8.2 within the context of off-design conditions, Woodward et al. (2005a) 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 above review 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.

9.4 Applicability of the Criteria

Perhaps the most direct and up to date investigation on the analysis of the IMO Manoeuvring Criteria are presented in a recent PhD Thesis, (Woodward, 2005) with the fundamental objective of making qualified assessment of the validity of the IMO manoeuvring criteria 'Resolution MSC.137(76)', when applied to pod-driven ships, (IMO, 2002).

In order conduct the analysis, Woodward (2005) developed validated simulation tools dedicated for pod-driven ships and used these tools to evaluate the validity of the existing criteria. In this process, semi-empirical tools capable of predicting the hull-form derivatives of typical pod-driven ship hull-forms were derived. Captive model tests were conducted using the OPTIPOD project hull-forms (a Ropax ship, a Cruise vessel, a Cargo ship and Supply vessel) and the results are used to validate the derived semi-empirical tools. The estimated values are demonstrated to make good agreement with the measured results.

The effect of an inclined flow on the propeller is investigated and a practical method for predicting the generated forces and moments on the individual blade as well, as the whole propeller, is derived in order to make a critical analysis of the unsteady forces. This is combined with an other practical method for predicting the lift and drag characteristics of the pod-body to describe a continuous function that predicts the global forces and moments acting on an azimuthing pod-drive at any angle of attack and load condition. The continuous function is validated with suitable model testing showing very good results.

A philosophy is adopted to develop a suite of time-domain simulation tools together with a Runge-Kutta methodology for integrating the resulting functions that can be used to simulate the manoeuvring behaviour of pod-driven ships. The developed tools are validated by comparison with the results of free-running model tests for each of the representative ships. In all cases, good agreement is observed between the predicted and measured response. Also, in all cases, good agreement is observed between the predicted and measured pod loads; including dynamic effects.

The turning ability criterion is evaluated using systematic simulation of manoeuvres. For each of the ships the advance and tactical diameter criteria are investigated for a range of applied helm angles. In each case it is clear that the turning parameters reduce with increased applied helm angle. The advance of one ship tested showed some increase between the 20^o and 35^o applied helm angle however, no specific risk of collision is relevant as all forward speed was completely lost; see Fig. 9.1 (Ship A). In all cases the turning parameters increase rapidly with reduced applied helm angle. And in all cases, there is little to be gained for applied helm angle above 35^o. All test results indicate that a 35^o applied helm angle is entirely appropriate for testing the turning ability of pod-driven ships.

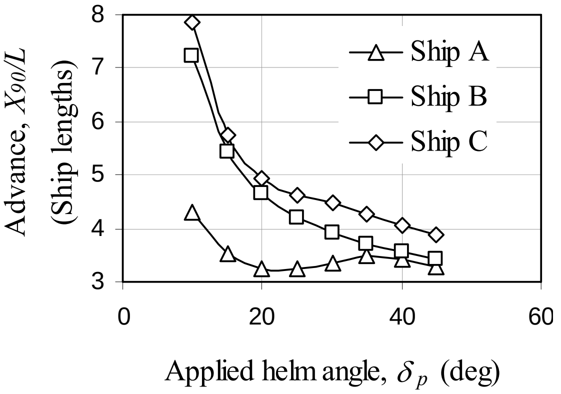

Figure 9.1- Assessment of advance criterion.

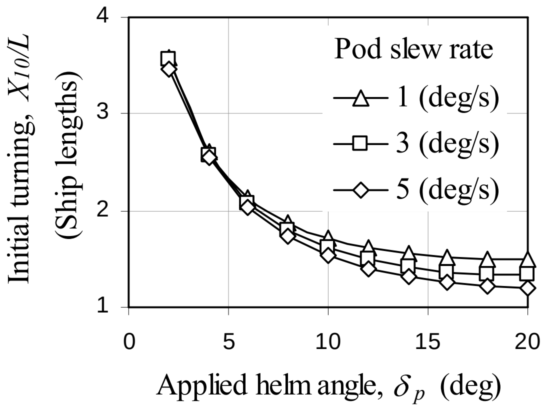

Figure 9.2- Assessment of initial turning criterion.

The initial turning ability criteria are evaluated using systematic simulation of manoeuvres. For each of the ships tested the initial turning for various applied helm angles and for different pod slewing rates is calculated. All cases demonstrate reduced advance for increased applied helm angle; showing a significantly more pronounced relationship for applied helm angles of less than 10°. Also, all cases demonstrate increased variation with respect to slew rate for applied helm angles above 10°; see Fig. 9.2. All test results indicate that a 10° applied helm angle is entirely appropriate for testing the initial turning ability of pod-driven ships.

The yaw-checking criterion is evaluated using systematic simulation of manoeuvres. IMO criteria maps are used to compare lines of constant criteria values with lines of constant phase margin. In all cases it is observed that the lines of constant phase margin and the lines of constant IMO overshoot criteria follow very similar contours; see Fig 9.3. All test results indicate that the 10/10 and 20/20 test criteria are entirely appropriate for testing the yaw-checking ability of pod-driven ships as they approximate well the -5° phase margin.

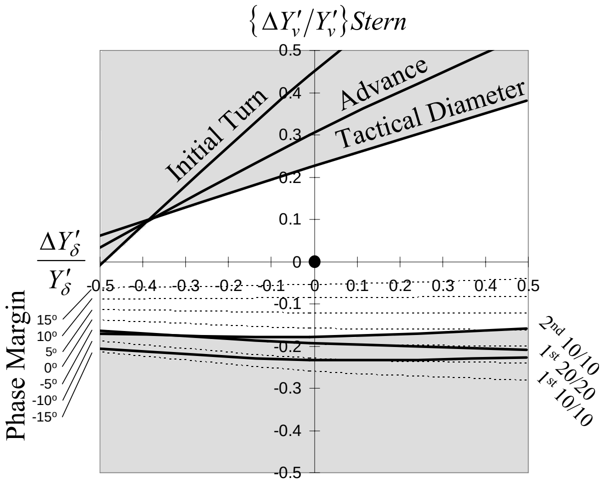

Figure 9.3- Assessment of the yaw-checking criterion.

The stopping ability criteria are evaluated using systematic simulation of manoeuvres. The stopping criterion is investigated together with other method of stopping pod-driven ships. The investigation finds that other operations exist that can stop a pod-driven ship more efficiently and perhaps with less load on the propeller. However, the investigation also finds that the IMO stopping ability criterion is still perfectly valid for pod-driven ships.

9.5 Concluding Remarks

Based upon the analysis of the work reviewed in the above the Committee concludes that the performance limits given by the IMO manoeuvring criteria provide an adequate benchmark to compare all ships, regardless of propulsion type however the application of specific helm angle is less well defined – an azimuthing podded propulsor can be turned to any helm angle with no specific definition for the angle of maximum force.

The Committee reaches the conclusion that, the IMO manoeuvring criteria ‘Resolution MSC.137(76)’, provide equivalent information about the manoeuvring response of pod-driven ships as for conventionally propelled ships; and can thus be applied directly.

The Committee also points out that hull-forms suited to the application of pods can have poor course stability characteristics. Failure to address this at the preliminary design stage can result in a ship that cannot meet the yaw-checking criteria. However, this is primarily a design issue and the existing IMO criteria provide an adequate benchmark to impede the development of poor designs.

10. SPECIAL APPLICATIONS FOR PODDED PROPULSION

10.1 Introduction

In this section a brief review of the special applications of podded propulsion is presented.

10.2 Double Acting Tanker (DAT)

The earlier mentioned (Section 4.3), unique double acting concept allows the vessels to travel ahead in ice-free water using a bulbous bow optimised for open seas. When sailing in ice, however, the vessel travels astern, using its reinforced stern to break the ice.

Sasaki et al. (2002 and 2004) reported on comprehensive model tests conducted during the initial design stage involving: propeller and podded propulsor open water tests; resistance and self-propulsion tests; streamline and wake measurements; cavitation; manoeuvring; and ice tests. The correlation of the open sea speed-power characteristics between the predictions based on the SSPA method and trial results was fairly good indicating that the predicted speed is about 0.3 knot higher or the predicted power about 7% lower than measured at trials.

Tragardh et al. (2004) reported that, based on the reverse spiral test analysis for going ahead condition, unusually large loop width (12.5 deg) was found and a fin at the bottom of the pod was fitted to improve the going ahead course stability significantly. The correlation between the free manoeuvring tests and sea trials at loaded going ahead condition was found to be reasonably good while the vessel meeting the IMO criteria (IMO, 1993). The astern manoeuvring performance was demonstrated by the pull-outs from the turning circles and the degree of instability observed was considered acceptable based on the IMO criteria.

10.3 CRP-Podded Propulsion Systems

Hybrid CRP-Podded Propulsor. One of the innovative applications of podded propulsion systems in the last decade has been its combined use with a conventional drive system in a contra rotating mode. In this hybrid system the forward propeller is driven by a conventional shaft and a puller-type azimuthing podded propulsor complements the forward propeller in a contra-rotating manner. The development of this concept has been carried out in a number of laboratories worldwide. The main attraction of this application is to combine the well-known advantages of a CRP (around 10% efficiency improvement, split power transmission) and that of a podded drive system (manoeuvrability) in a less complex manner compared to a conventional CRP drive. The application is particularly attractive for large displacement and fast modern ships. For example, Kim et al. (2002) reported on the application of this propulsion system to an Ultra Large Container Vessel (ULCV) through a comparative experimental investigation including single screw and twin screw options.

In this hybrid propulsion system, the problem of power prediction and the design of conventional (forward) propeller and (aft) podded propulsor are complicated tasks due multitude of different parameters which have impact on the propeller design and complex hydrodynamic characteristics of this system. Even propulsion tests for the preparation and formulation of the initial data to design the podded propeller is rather complicated. Wake on the aft propeller depends on the geometry of the forward propeller and state-of-the-art, at the moment, suggests that the input data for the aft propeller design can be obtained from the results of propulsion tests with the forward stock propeller of equivalent diameter in the absence of podded propulsor at the aft, Varis (2005). The procedures for power prediction and propeller design for these hybrid propulsion systems at the moment are not developed properly although there are encouraging attempts.

Bushkovsky et al. (2003a) presented a computational method for the calculation of unsteady forces and torque induced on the aft propeller of a hybrid CRP-Pod system where the pod can be set at a desired helm angle. The problem was then solved for the case of non-uniform wake field on the pod propeller. The steady and unsteady forces and moments induced on both propellers are determined in the calculations and the accuracy of the developed computational method is confirmed by published experimental data.

Investigating different hydrodynamic aspects, Bushkovsky et al. (2004) discussed propeller design, periodic forces, crash stop and cavitation aspects of these hybrid propulsion systems. The study claims that while it is advisable to conduct propulsion predictions using associated model tests, which include the effect of passive components (pod-housing), this is not enough for accurate propeller design since the impact of pod-housing on the propeller is not separable. The study shows that periodic forces have a wider spectrum of harmonics where the frequencies associated with interaction between the two propellers of the podded-CRP can be described by a proposed formula.

The cavitation aspect was briefly mentioned in Bushkovsky et al. (2004) and described in more detail in Frolova et al. (2004). It was noted that hub vortex cavitation emanating from the fore propeller interacts with the pod propeller blades at the aft propeller leading to a potentially dangerous erosion problem. It was found necessary to apply measures to destroy the hub vortex.

In an experimental study, Go et al. (2004) investigated the relations of power and rpm distribution, effect of pod (aft) propeller on the main (fore) propeller, effect of advance ratio on the power ratio and effect of inflow uniformity on the power ratio of the pod-CRP system for an Ultra Large Container Carrier (ULCC). The same study also made emphasis on the lack of a standard procedure for the powering performance prediction of CRP systems in general and a new method has been proposed for the subject ULCC driven by hybrid CRP podded propulsor. In this method, supported by the experimental findings, the main propeller is regarded as a single propeller and the pod propeller is treated as a subordinate device linked to the main propeller. Hence, the open water test results of the main propeller alone are used to define the self-propulsion factors. Pod drag correlation is considered in the revised thrust deduction factor. In wake scaling, an acceleration factor is introduced to take account for the suction effect of the pod propeller like rudder retardation effect. The accuracy of the method relies on the reliable correlation of the pod housing drag and the acceleration coefficients which need systematic evaluation.

Varis (2005) reported on the overall results of the earlier mentioned (Section 4.1) *ENVIROPAX* project, investigating the hydrodynamic design aspects of hybrid CRP-Pod system. The results consider the effect of power distribution on the propulsion efficiency and propulsion performance of two different pod sizes, cavitation performance of the propellers in different conditions and pressure pulse levels on the hull. Series of model tests in conventional and depressurised towing tanks were conducted and these were supported by computational studies involving parametric investigations for main parameters of propellers, effective wake field, cavitation patterns and pressure level predictions.

As stated in Section 4.1, one of the main products of the *ENVIROPAX* project was the development of two 225m (L_{oa}) fast ferries. As reported by Ueda et al. (2004), the vessels were able of achieving a 32kts maximum trial speed. After 6 months of operations, the energy saving is reported at >13%. The previous one-way cruising time of 29hrs, with a conventional ferry, has been shortened to 20 hours.

At the beginning of the project development, the propulsion and cavitation performance of these ferries were investigated using experimental methods which formed the basis for the initial design of the hull form and propellers. In the detail design of the podded CRP system, CFD calculations using RANS were indispensable. The cavitation performance of the podded CRP was investigated in depressurised towing tank and the results were used to make the vibration countermeasures.

At the sea trials, several full-scale measurements were carried out including cavitation observations. The pressure fluctuations measured in full-scale show good agreement with those measured in model tests. Vibrations were measured and the effect of vibration countermeasures has been confirmed that corresponds exactly to prior estimations at the sea trials. These counter measures included the installation of small rudders at the stern in addition to the podded propulsor to steer the vessel at high speed instead of using the podded drive.

<u>Pure CRP-Podded Propulsor.</u> As mentioned in Section 4.1, as part of the Japanese R&D project '*Super-Ecoship*', a new podded CRP system which accommodates a pure CRP at one end of the pod has been developed and full-scale tests of a 2x1250kW podded unit mounted on a special rig in a dry dock was tested in 2004; (RINA, 2005).

Within the framework of this project, Ukon et al. (2004) presented an experimental study describing a new 5-components balance to test such a propulsion system in open water and self-propulsion conditions and the results of some tests conducted with this propulsion system in the puller- and pusher-mode. Through a design case study for a coastal tanker, the paper demonstrated a promising propulsive performance over the same vessel propelled by conventional drive. Using the test results, self-propulsion factors and full-scale power predictions were performed based on the two well-known analysis methods: (i) Pod housing was treated as part of the hull as appendage; (ii) Pod housing was part of the propulsor. The differences in the self-propulsion factors and power predictions were noted and further investigation was requested for a ship model correlation procedures, particularly to predict the pod housing drag in full-scale for the tractor types.

This research study is also supported by numerical investigations conducted by Ohashi and Hino (2004) who used a RANS solver with an unstructured grid method and compared the predictions for the resistance, open water and self-propulsion characteristics with the model test results and reported good agreements for the pusher- and puller-modes.

10.4 Rim-Driven Podded Propulsor

The Rim-Driven Pod (RDP) concept integrates a ducted, multiple blade row propeller with a permanent magnet, radial flux motor rotor mounted on the tips of the propeller rotor blades and the motor stator mounted within the duct. van Blarcom et al. (2002) claim that this concept, when compared to a hub-driven pod, offers hydrodynamic advantages: required thrust with a smaller pod; higher propulsive efficiency; reduced unsteady hull pressure levels; reduced vulnerability to performance degradation both straight ahead and at steering angles; higher ship speeds with acceptable cavitation and no risk of cavitation erosion; more flexibility in hull design at the aft end due to its much smaller size.

Lea et al. (2002) presented the results of the model test programme conducted with a 1/25 scale model of an RDP designed for a 24.5 kts *Panamax* cruise vessel. The test programme included open water, self-propulsion and cavitation tests with a single RDP scale-model fabricated geometrically similar to the full-scale except for the PM motor/rotor gap, strut and the method of driving the motor.

Eaton et al. (2003) described a coherent scaling methodology for pod powering performance that can be applied to RDP as well as other simple and complex propulsion types. The inclusion of a surface roughness model enables this method to handle a broad range of model and full-scale fabrication classes. Addition of Re number dependent viscous drag models facilitates its application to a wide range of propulsor configurations including ducted types. Also, Eaton and Billet (2004), presented a review of their preliminary and detailed hydrodynamic design method for RDPs. In a later paper by van Blarcom et al. (2004) it was reported that a 1.6MW RDP demonstrator completed in-air testing and the plans were for at-sea testing to commence in 2006.

10.5 New Podded Propulsors for Smaller Power Range

Kaul (2004) reports on two types of new podded propulsors for the lower power range of 1-5MW. These are abbreviated as *SEP* and *SCD*. The *SEP* has the same features and principles of the well-known *SSP* system with tandem propellers except the cooling system which has an innovative feature where the rotor is cooled by the flow through the hollow bored propeller-motor shaft. The *SCD* is an optimised intermediate solution between mechanical rudder-propeller and electric podded propulsor to take advantage of diesel-electric propulsion.

Kaul (2004) presented a combined approach to develop a reliable performance prediction in full-scale due to complex feature of the *SEP*. This involved: standard towing tank tests with solid shaft model; wind tunnel and cavitation tests with a special hollow shaft model; CFD calculations in model and full-scale to take care of Re number effects and finally full-scale prototype test with the *SEP* unit designed for an ice-class research vessel at a floating dry dock for torque absorption, cooling ability and vibration levels.

10.6 Concluding Remarks

During the last decade, rapid developments have been observed in real and concept applications of various types of podded propulsors for ships. These developments have initiated vast research programmes directed to the perfection of propulsion performance including cavitation, pod designs and the developments of special pod applications. There are also concept podded propulsor developments with special novel features.

The special features of these applications require rather sophisticated experimental facilities, techniques and more support from CFD procedures and full-scale data. While the ITTC is currently concentrating on the conventional applications, the review of developments for these special applications should not be overlooked.

11. TECHNICAL CONCLUSIONS

1. During the last decade, rapid developments have been observed in the concept and real design applications of various types of azimuthing podded propulsion systems for ships. These developments have initiated vast research programmes directed to the

perfection of propulsion performance including cavitation; pod designs by considering maximum loading at off-design conditions; developments of special pod applications for ice class ships (DAT) and high speed ships using the CRP concept.

2. The Committee have made efforts to develop procedures on podded propulsor tests and full-scale propulsion predictions as well as on model-scale cavitation tests. These efforts have resulted in the following conclusions:

a) Although there are other options, common practice in propulsion predictions implies that a podded propulsor is considered as a unit with its propeller(s), housing and other components attached to the unit. This requires the use of a special podded propulsor testing device and the conduct of tests with this device to predict the unit performance in open water.
b) The unit open water performance data together with the data to be obtained from model hull resistance test (without the pod unit) and the self-propulsion test provide a basis for the prediction of the propulsion performance in full-scale.
c) In the above outlined procedure, even if the three sets of model test are consistent, there is still uncertainty associated with the prediction of the pod-housing drag in full-scale. The investigation of the Committee indicated that the differences in the various approaches used to predict this drag component are significant and require further investigation. Full-scale data to verify the impact of the different approaches is scarce. The Committee therefore is unable to formulate a single guideline for full-scale propulsion prediction at this stage.
d) The Committee recommends further collaborative work in the area of extrapolation involving pod manufacturers, testing facilities and other relevant participants. This work should investigate different approaches, including RANS based modelling of the housing drag, and the use of consistent model test data supported by reliable full-scale speed-power measurements.
e) The measurement of the propeller thrust at the pod unit provides invaluable information for the pod designer as well as for further propulsion prognosis. However, its measurement suffers from the “gap-effect” phenomenon and hence associated uncertainty, which requires further investigations to improve the reliability in measuring this thrust component.
f) The recommended procedure for model scale cavitation test and appearances is adapted from that for the conventional propeller with specific emphasis on the wake flow simulations for different pod configurations, different cavitation patterns on the pod and the relative position of the pod with respect to the inflow including small helm angle effects.
g) The proposed cavitation procedure is valid for operational conditions at straight ahead and slight off-course conditions at small steady helm angles. The cavitation performance in dynamic manoeuvring modes, particularly at large helm angles and in dynamically controlled mode can be of great interest but will require great care and further amendment of the procedure.

3. Off-design conditions are critical stages in the design and operation of podded propulsion systems since the loads on various components of the propulsors may reach maximum values at these conditions. The implication of these conditions should therefore be taken into account in both design and operation.

a) Off-design conditions for a pod-driven vessel can be associated with: ‘course keeping’ at small helm angles; ‘manoeuvring’ at large helm angles; ‘crash-stop’ using various means; and ‘acceleration/ deceleration’ modes of operations. In these conditions the unsteady nature of propeller operation will induce large blade forces and at the same time large spike loads will be induced on the pod-housing, due to dynamic manoeuvring behaviour, that will have significant implications for the structural design and may also impact on the vessel roll stability. The nature of the off-design loads are complex requiring further investigation of both an experimental and numerical nature to properly account for the unsteady nature of the propeller forces and other dynamic effects.

b) At the moment the application of CFD analysis to podded propulsors at off-design conditions has met with rather limited success and needs further development in the future. During the last three years, special dynamometers and investigations have been reported for load measurements on podded propulsors supported with flow visualisation in dynamic manoeuvring modes. These instrumentations make it possible to investigate pod hydrodynamics both in steady and unsteady conditions and to understand the physics of the complex off-design condition. However, there is a need for the development of procedures relating to the simulation and modelling of the off-design conditions as realistically as possible under laboratory conditions.

4. The performance limits given by the IMO Manoeuvring Criteria provide an adequate benchmark to compare all ships, regardless of propulsion type. However the application of specific helm angle is less well defined – an azimuthing podded propulsor can be turned to any helm angle with no specific definition for the angle of maximum force.

a) Dedicated simulation studies and the limited amount of reported manoeuvring tests with podded propulsor driven ships in full-scale suggest that the IMO manoeuvring criteria ‘Resolution MSC.137(76)’, provide equivalent information about the manoeuvring response of pod-driven ships as for conventionally propelled ships; and can thus be applied directly.

b) Similar studies indicate that hull-forms suited to the application of pods can have poor course-stability characteristics. Failure to address this at the preliminary design stage can result in a ship that can not meet the yaw-checking criteria. However this is primarily a design issue and the existing IMO criteria provide an adequate benchmark to impede the development of poor designs.

12. REFERENCES AND NOMENCLATURE

12.1 References

Atlar, M., Clarke, D., Glover, E.J., McLean, D., Sampson, R. and Woodward, M.D., [Editors], 2004, 1st T-POD, University of Newcastle, UK.

Bjarne, E.V., 1982, “Comparison of Cycloidal Propeller with Azimuth Thruster With Regard to Efficiency, Cavitation and Noise”, Propulsion of Small Craft Propellers, Sterngears, Engines and Installation Conference, November.

Bretz, E.A., 2004, “Super Conductors on the High Seas”, 23rd IEEE Spectrum, January.

Bushkovsky, V.A., Moukhina, L.A. and Yakolev, A.Yu., 2003a, “Calculation of Propellers Interaction in Contra-Rotating Concept” N&SN 2003, Saint-Petersburg, Russia, pp. 276-283.

Bushkovsky, V.A, Pustoshny, A.V., Vasiliev, A. and Veikonheimo, T., 2003b, “A Crash-stop Study for An Azipod-propelled Vessel”, FAST 2003, Naples, Italy, Vol. 2, pp. 1-6.

Bushkovsky, V.A., Frolova, I.G., Kaprantsev, S.V., Pustoshny, A.V., Vasiljev, A.V., Jakovlev, A.J. and Veikonheimo, T., 2004, “On the Design A Shafted Propeller Plus Electric Thruster Contra-Rotating Propulsion Complex", 1st T-POD, University of Newcastle, UK, pp. 247-261.

Cheng, B. and Stern, F., 1998, "Computational Fluid Dynamics of Four-Quadrant Marine Propulsor Flow", In: Journal of Ship Research, December, Vol. 43, No. 4, pp. 218-228.

Chicherin, I.A., Lobatchev, M.P., Pustoshny, A.V. and Sanchez-Caja, A., 2004, "On a Propulsion Prediction Procedure for Ships with Podded Propulsors Using RANS-Code Analysis", 1st T-POD, University of Newcastle, UK, pp. 223-236.

Clarke, D., 1992, "The manual steering criterion based upon phase margin", PRADS 1992, Newcastle-upon-Tyne, UK, Vol. 1, pp. 266-283.

Clarke, D. and Yap, M. L. R., 2001, "A multi-criteria view of the IMO manoeuvring requirements", Trans. RINA, Vol. 143, pp. 98-110.

Daniel R.J., 1984, "Mine Warfare Vessels and Systems", Mines Warfare Vessels and Systems Symposium, June, RINA, London, Vol. 1, Paper 1.

Eaton, J.E. and Billet, M.L., 2004, "Pod Propulsion Research and development at ARL-Penn State", 1st T-POD, University of Newcastle, UK, pp. 89-106.

Eaton, J.E., Praefke, E. and Mewis, F., 2003, "Enhanced Performance Scaling Methodology", FAST 2003, Naples, Italy, Vol. 1, pp. 17-26.

FASTPOD, 2001, "Fast Ship Applications For Pod Drives", Annex 1, Description of Work, European Commission RTD FP5 Project, GRD2-2001-50063, University of Newcastle upon Tyne (Co-ordinator).

Friesch, J., 2001, "Investigations of Podded Drives in a Large Cavitation Tunnel", PRADS 2001, Shanghai, China, Vol. 2, pp. 749-756.

Friesch, J., 2004, "Cavitation and Vibration Investigations For Podded Drives", 1st T-POD, University of Newcastle, UK, pp. 387-399.

Frolova, I., Kaprantsev, S., Pustoshny, A.V. and Veikonheimo, T., 2004, "Investigation of Cavitation For Contra-Rotating Propulsor – Propeller on Shaft Plus Pulling Azipod", PRADS 2004, Lubeck, Germany.

Go, S., Seo, H. and Chang, B.J., 2004, "Study on the Powering Performance Evaluation For the CRP-Pod Propulsion Ships", 1st T-POD, University of Newcastle, UK, pp. 277-287.

Grygorowicz, M. and Szantyr, J.A., 2004 "Open Water Experiments with Two Pod Propulsor Models", 1st T-POD, University of Newcastle, UK, pp. 357-370.

Hamalainen, R. and Van Heerd, J., 2001, "Triple pod propulsion in the world's largest ever cruise liner", PRADS 2001, Shanghai, China, Vol. 2, pp. 757-766.

He, M., Veitch B., Bose N., Bruce C. and Liu P., 2005, "Numerical Simulations of Propeller Wake Impacting on A Strut", CFD2005 (*To be presented*), St John's, NL Canada, 7p.

Heinke, H.J., 2004, "Investigation about the Forces and Moments at Podded Drives", 1st T-POD, University of Newcastle, UK, pp. 305-320.

Holtrop, J., 2001, "Extrapolation of propulsion tests for ships with appendages and complex propulsors", Marine Technology, 38 (3), pp. 145-157.

IMO, 1993, "IMO Resolution A.751 (18): adopted on 4 November 1993 (agenda item 11): Interim Standards For Ship Manoeuvrability. [Including] Explanatory notes ... MSC/CIRC 644", International Maritime

Organisation (IMO). UK; Marine Safety Agency, for the IMO, Feb 1995, [48] p., Resolutions and other decisions (resolutions 733-779), IMO, 510 p.

IMO, 2002, "Standards For Ship Manoeuvrability", International Maritime Organisation, Maritime Safety Committee (IMO MSC), 76th Session, Agenda Item 23, Report on the Maritime Safety Committee on its Seventy-Sixth Session, MSC 76/23/Add.1, 18 Dec 2002, Annex 6, Resolution MSC.137(76)(Adopted on 4 December 2002), Page 1 - Page 6 [MSC\76\23-ADD.1.DOC, in PDF format, also paginated as pp. 37-42.

Islam, M., Veitch, B., Bose, N. and Liu, P., 2005a, "Numerical Study of Effects of Hub Taper Angle on the Performance of Propellers Designed for Podded Propulsion Systems", Marine Technology (*To be published*), 11p.

Islam, M. Veitch, B., Bose, N. and Liu, P. 2005b, "Cavitation Characteristics of Pushing and Pulling Podded Propellers With Different Hub Taper Angles", The 7th MHSC (*To be presented*), Halifax, NS Canada, 7p.

Islam, M., Molloy, S., Veitch, B., Bose, N. and Liu, P., 2005c, "Numerical and Experimental Studies of Pod-Strut Geometry on Podded Propellers Performance", CFD 2005 (*To be presented*), St. John's, NL Canada, 17p.

ITTC, 1999, "The Specialist Committee on Unconventional Propulsors, Final Report and Recommendations to the 22nd ITTC", 22nd ITTC, Seul-Shanghai, Vol 2, p. 311-344.

ITTC, 2002a, "Model-Scale Cavitation Test", 23rd ITTC, Venice, ITTC Recommended Procedures, Procedure 7.5-02-03-03.1, Rev 01, pp. 1-9.

ITTC, 2002b, "Open Water Test", 23rd ITTC, Venice, ITTC Recommended Procedures, Procedure 7.5-02-03-02.1, Rev 01, pp. 1-9.

ITTC, 2002c, "The Propulsion Committee, Final Report and Recommendations to the 23rd ITTC", 23rd ITTC, Venice, Vol 1, pp. 8-151.

ITTC, 2002d, "Description of Cavitation Appearances", 23rd ITTC, Venice, ITTC Recommended Procedures, Procedure 7.5-02-03-03.1, Rev 01, pp. 1-7.

ITTC, 2002e, "Podded Propulsors Tests and Extrapolation", 23rd ITTC, Venice, ITTC Recommended Procedures, Procedure 7.5-02-03-01.3 (Interim), Rev 00, pp. 1-11.

ITTC, 2005, "Podded Propulsor Model-Scale Cavitation Test", 24th ITTC, Edinburgh, ITTC Recommended Procedures, Procedure 7.5-02-03-03.5, Rev 00, pp. 1-12.

Jessup, S., Hesnakas, C.C., Fry, D., Donnelly, M., Black, S. and Park. J., 2004, "Propeller Performance at Extreme Off-design Conditions", 25th Symposium on Naval Hydrodynamics, St.John's, Canada.

Junglewitz, A., Moctar, O. and Franic, O., 2004a, "Podded Rudders", 1st T-POD, University of Newcastle, UK, pp. 401-418.

Junglewitz, A., Moctar, O. and Stadie-Frohbos, G., 2004b, "Loads on Podded Drives", PRADS 2004, Lubeck, Germany.

Kaul, S., 2004, "New Podded Drives For the Power range of 1-5 MW", 1st T-POD, University of Newcastle, UK, pp. 61-72.

Kempf, G., 1932, "Measurements of the propulsive and structural characteristics of ships", SNAME Trans., Vol. 40, pp. 45-57.

Kim, S.E., Choi, S.H. and Veikonheimo, T., 2002, "Model Tests on Propulsion Systems for Ultra Large Container Vessel", ISOPE-2002, Kitakyushu, Japan.

Kurimo, R., 1998, "Sea trials experience of the first passenger cruiser with podded propulsors", PRADS 1998, Hague, Netherlands, pp. 743-748.

Kurimo, R. and Byström, L., 2003, "Manoeuvring With Pods: Model Tests and Sea Trials of M/S Costa Atlantica", IMDC'03, Athens, Greece, Vol. 2, pp. 163-177.

Kurimo, R., Pustoshny, A.V. and Syrkin, E., 1997, "AZIPOD Propulsion For Passenger Cruisers", NAV&HSMV Intl. Conference, Sorrento, Italy.

Lea, M., Thompson, D., Van Blarcom, B., Eaton, J., Richards, J. and Friesch, J., 2002, "Scale Model Testing of a Commercial Rim-Driven Propulsor Pod", SNAME Annual Meeting.

Lepeix, R., 2001, "Hydrodynamic Trends in Hull Lines of Podded Driven Large Cruise Vessels", PRADS 2001, Shanghai, China, Vol. 2, pp. 767-766.

Lobachev, M.P. and Tchitcherine, I.A., 2001, "The Full Scale Estimation for Podded Propulsion System by RANS Method" Lavrentiev Lectures, St. Petersburg, Russia, 19-21 June, pp. 39-44.

MacNeil, A., Taylor, R., Molloy, S., Bose, N., Veitch, B, Randell, T. and Liu, P., 2004, "Design of A Model Pod Test Unit", 1st T-POD, University of Newcastle, UK, pp. 447-457.

Matilla, M and Veikonheimo, T., 2004, "Letter to 23rd ITTC Azimuthing Podded Propulsion Committee", Letter, Ref INMT2004-000008, ABB Oy, Marine & Turbocharging.

Mewis, F., 2001, "The Efficiency of Pod Propulsion", HADMAR'2001, Bulgaria, Vol. 3.

Mewis, F. and Praefke, E., 2003, "A Method for Scale Effect Corrections on Pod propulsor Open Water Characteristics from Model to Full Scale", Jahrbuch der Schiffbautechnischen Gesellschaft, 97, Band 2003, Springer Verlag Berlin Heidelberg, New York.

Molloy, S. and Bose, N., "Ship Powering Prediction from Self-Propulsion Load Varying Tests", International Symposium of Ship Propulsion (Lavrentiev Lectures), State Marine Technical University, St. Petersburg, Russia, pp. 133-142.

Molloy, S., Bose, N., Veitch, B., Taylor, R. and MacNeill, A. 2004, "Systematic Variation of Podded Propulsor Models", 1st T-POD, University of Newcastle, UK, pp. 459-464.

Moukhina, L.A. and Yakovlev, A.Yu., 2001. "Calculations of Forces on the Propeller at Vessels Manoeuvring", N&SN, St. Petersburg, Russia, pp.70-77.

Nakatake, K., Ando, J., Yoshitake, A., Sato, Y. and Tamashima, M., 2004, "On Propulsive Performance of a Small Bulk-Carrier Model with Twin Podded Propellers", 1st T-POD, University of Newcastle, UK, pp. 501-512.

Nomoto, K., Taguchi, T., Honda, K. and Hirano, S., 1957, "On the Steering Qualities of Ships", International Shipbuilding Progress, Vol. 4, No 35, pp. 354.

Ohashi, K. and Hino, T., 2004, "Numerical Simulations of Flows Around a Ship with Podded Propulsor", 1st T-POD, University of Newcastle, UK, pp. 211-221.

OPTIPOD, 1999, "Optimal Design and Implementation of Azimuthing Pods For the Safe and Efficient Propulsion of Ships -Annex 1 (Description of work)", European Commission RTD FP5 project, GRD1-1999-10294, Chantiers de l'Atlantique (Co-ordinator).

Pitts, E.C. and Dorey, A.L., 1984, "Experience with the design of GRP MCM vessels", Mines Warfare Vessels and Systems Symposium, June, RINA, London, Vol. 2, Paper 2.

PODS in Service, 1999, "PODS in Service" Annex 1, Description of Work, European Commission JIP FP5 Project, GRD1-1999-10395, MARIN (Co-ordinator).

Pustoshny, A.V., 1990, "Trends of Application of Cycloidal Propellers for Dynamic Positioning Vessels", Methodological Seminar on Ship Hydrodynamics, October, Vol. 1, No. 44, Varna, Bulgaria.

Pustoshny, A. V. and Kaprantsev, S. V., 2001, "Azipod Propeller Blade Cavitation Observations During Ship Manoeuvring", CAV 2001, Pasadena, USA.

Pustoshny, A.V. and Semionicheva, E.Ja., 1996, "Minehunters: Choice of Propulsor with Improved Cavitational Characteristics at Positioning Mode", N&SN, St. Petersburg, Russia.

RINA, 2004, "Genesis of a Queen: Cunard Line's Queen Mary 2", The Naval Architect, Pub: RINA.

RINA, 2005, "Construction of First Eco-Ship Draws Nearer", The Naval Architect, June, RINA, pp. 44-45.

Sánchez-Caja, A., Ory, E., Salminen, E., Pylkkänen, J. and Siikonen, T., 2003, "Simulation of Incompressible Viscous Flow Around a Tractor Thruster in Model and Full Scale". The 8th International Conference on Numerical Ship Hydrodynamics, Busan, Korea.

Sasaki, N., Laapio, J., Fagerstrom, B.,Juurma, K. and Wilkman, G., 2004, "Full Scale Performance of Double Acting Tankers *Mastera & Tempera*", 1st T-POD, University of Newcastle, UK, pp. 155-172.

Sasaki, N., Laapio, J., Fargerstrom, B. and Juurmaa, K., 2002, "Model Tests of Ice Going Acting Aframax Tanker", Proc. of 7th Canadian Marine Hydrodynamics and Structure Conference, Vancouver, Canada.

Smith, J., 2002, "Escort tugs - Dynamic Analysis of The Indirect Mode", Department of Marine Technology, Post Graduate Conf., Session 1, Paper 2, 10 p

Stettler, J.W. and Hover, F.S., 2004, Triantafyllou, M.S., 2004, "Preliminary Results of Testing on the Dynamics of an Azimuthing Podded Propulsor Relating to Vehicle Manoeuvring", 1st T-POD, University of Newcastle, UK, pp. 321-338.

Szantyr, J.A., 2001a, "Hydrodynamic Model Experiments with Pod Propulsor", International Symposium of Ship Propulsion (Lavrentiev Lectures), State Marine Technical University, St. Petersburg, Russia, pp. 95-104

Szantyr, J.A., 2001b, "Hydrodynamic Model Experiments with Pod Propulsor", Oceanic Engineering International, Vol. 5, No.2, p. 95-103

Toxopeus, S. and Loeff, G., 2002, "Manoeuvring Aspects of Fast Ships with Pods", HIPER 2002, Bergen, Norway, pp. 392-406.

Tragardh, P., Lindell, P., and Sasaki, N., 2004, "Double Acting Tanker – Experiences From Model Tests and Sea Trials", 1st T-POD, University of Newcastle, UK, pp. 173-186.

Ueda, N., Oshima, A., Unseki, T., Fujita, S., Takeda, S. and Kitamura, T., 2004, "The First Hybrid CRP-POD Driven Fast ROPAX Ferry in the World", Mitsubishi Heavy Industries Ltd, Technical Review, Vol. 41, No. 6, pp. 1-4.

Ukon, Y., Fujisawa, Y., Ohashi, K. and Hino, T., 2003, "Hydrodynamic Performance of Podded Propulsors", (Japanese), Trans. of of

West-Japan Society of Naval Architects, No. 106, pp. 146-156.

Ukon, Y., Ohashi, K., Fujisawa, J. and Hasegawa, J., 2004, “Propulsive Performance of a Contra-Rotating Podded Propulsor”, 1st T-POD, University of Newcastle, UK, pp. 289-302.

van Blarcom, B., Franco, A., Lea, M., Peil, S. and Van Dine, P., 2004, “Rim-Drive Propulsion-Improving Reliability and Maintainability Over Today’s Pods”, 1st T-POD, University of Newcastle, UK, pp. 73-88.

van Blarcom, W., Hanhinen, J. and Mewis, F., 2002, “The Commercial Rim-Driven Permanent Magnet Motor Propulsor Pod” SNAME Annual Meeting, September.

van Rijsbergen, M. and Holtrop, J., 2004, “Investigations on a pod open water test set-up”, MARIN Internal Report, No: 16115-1-DT.

van Terwisga, T., Quadvlieg, F. and Valkhof, H., 2001, “Steerable Propulsion Units: Hydrodynamics Issues and Design Consequences”, Paper Written on the Occasion of the 80th Anniversary of Schottel GmBH & Co., 11 August.

Varis, J., 2005, “CRP AZIPOD Propulsion Operational Experience”, Conference Papers of The Motor Ship’s 27th Annual Marine Propulsion Conference, Bilbao, pp. 57-70.

Wang, D., Atlar, M., Glover, E.J. and Paterson, I., 2004, “Experimental Investigation of Flow Field Around a Podded Propulsor Using LDA”, 1st T-POD, University of Newcastle, UK, pp. 483-498.

Woodward, M.D., Clarke, D. and Atlar, M., 2002a, “An investigation into The Course Stability and Control of A Fast, Pod-Driven Ropax”, HIPER 2002, Bergen, Norway, pp. 437-447.

Woodward, M.D., Clarke, D., Atlar, M., Weede, H., Trägårdh, P., Kanar, J., Helasharju, H., Laamanen, T., Varoma, M., Van Berlekom, W., Hansson, H., Magnusson, K. and Allenstöm, B., 2002b, “Final Non-Confidential Report on Safety and Risk Analysis”, University of Newcastle, EU RTD FP5 OPTIPOD GRD1-1999-10294, WP3-DOC-0091.

Woodward, M.D., Clarke, D. and Atlar, M., 2003), “On the manoeuvring prediction of pod-driven ships”, MARSIM'03, Kanazawa, Japan, Vol. 2, Paper 7, pp. 1-9.

Woodward, M.D., Atlar, M. and Clarke, D., 2004, “A comparison of the stopping modes for pod-driven ships”, 1st T-POD, University of Newcastle, UK, p. 339-356.

Woodward, M.D., Atlar, M. and Clarke, D., 2005a, “Comparison of stopping modes for pod-driven ships by simulation based on model testing”, Proc. IMechE. Vol. 219 Part M: J. Engineering for the Marine Environment, 18 p.

Woodward, M.D., Atlar, M. and Clarke, D., 2005b, “Manoeuvring induced loads on fast pod drives”, FAST 2005, St. Petersburg, Russia, 8 p.

Woodward, M.D. 2005, “Control and Response of Pod-Driven Ships”, School of Marine Science and Technology, University of Newcastle, PhD Thesis, 219 p. [Commercial in Confidence]

12.2 Nomenclature

CAV	International Symposium on Cavitation
FAST	International Conference of Fast Sea Transportation
HADMAR	International Conference on Hydrodynamics and Aerodynamics in Marine Engineering

HIPER	International Euro Conference on High Performance Marine Vehicles
HSMV	Symposium on High Speed Marine Vehicles
IMDC	International Marine Design Conference
ISOPE	International Offshore and Polar Engineering Conference
MARSIM	International Conference on Marine Simulation and Ship Manoeuvrability
NAV	International Conference on Ship and Shipping Research
N&SN	International Conference on Navy and Shipbuilding Nowadays
PRADS	International Symposium on Practical Design on Ships and Other Floating Structures
T-POD	International Conference on Technological Advances in Pod Propulsion