The Commercial Rim-Driven Permanent Magnet Motor Propulsor Pod

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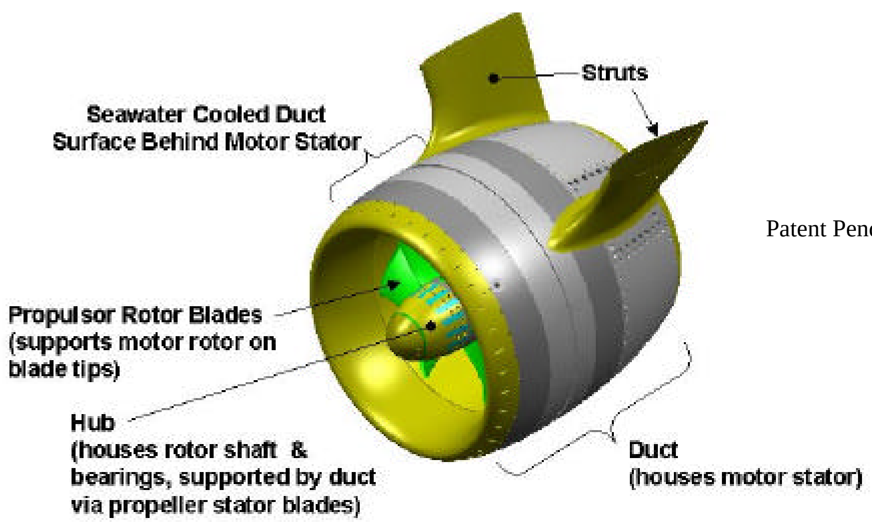

Patent Pending

ABSTRACT

Podded propulsion is gaining more widespread use in the marine industry and is prevalent in newer cruise ships in particular. This propulsion system can provide many advantages to the ship owner, including improved propulsion efficiency, arrangement flexibility, payload and harbor maneuverability. A new unique podded propulsor concept is being developed that allows optimization of each element of the system. The concept integrates a ducted, multiple blade row propulsor with a permanent magnet, radial flux motor rotor mounted on the tips of the propulsor rotor blades and the motor stator mounted within the duct of the propulsor. This concept, designated a Commercial Rim-Drive Propulsor Pod (CRDP), when compared to a conventional hub-drive pod, offers improved performance and attributes in a number of areas, including: smaller weight and size, and equal or improved efficiency and efficiency bandwidth, cavitation and hull unsteady pressures. The combination of these CRDP attributes and performance parameters could allow the ship designer greater flexibility to provide improved ship performance at reduced cost, as compared to that of a hub-drive pod. The advantages extend across the entire operating range, from sea trial to off design conditions. The advantages when compared to a hub-drive pod could allow a CRDP to achieve higher ship speeds, or to be applied to a wider range of platforms, or to extend the operating envelope of those platforms. The present paper discusses the CRDP's advantages for both the ship designer and operator, compared to currently available hub-drive pods.

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INTRODUCTION

General Dynamics Electric Boat (EB) has developed a commercial rim-driven propulsor pod (CRDP, patents pending) and recently completed hydrodynamic model testing of an 18MW CRDP at 1/25 model scale to demonstrate performance potential [1]. Testing included powering (open water and self propulsion) and measurement of cavitation and hull pressure fluctuations (at 0^{o} and 8^{o} angle of incidence). The purpose of this paper is to expand on those test results and provide an assessment of the benefits of the CRDP for a variety of platforms.

Principles Of CRDP Design

The CRDP design balances the hydrodynamic performance and structural integrity of the propulsor while integrating the motor. The key hydrodynamic performance parameters for the CRDP are high efficiency, good cavitation performance and off-design performance while maintaining a compact overall size (length and diameter), light weight and structural integrity. One of the main advantages of a rim-drive design is the mounting of the motor rotor on the rim attached to the propulsor rotor. This allows the motor to produce a higher torque, thus enabling operation at a low RPM. The low RPM results in low relative velocity over the rotor blades, which contributes to good efficiency and cavitation performance. An additional advantage is reduced flow distortion due to the strut being located outside the propeller flow stream. These advantages are enabled by radial field PM motors.

The strut and duct of the CRDP are designed within the constraints imposed by the motor. The motor requires provisions for both cooling and electrical connections and cabling, which affect the strut chord length and duct geometry. Motor cooling is provided via seawater flow through the gap between the rotor and stator and seawater flow over the outside surface of the duct immediately behind the motor stator. For maximum efficiency the strut span can be minimized, but must be sufficient to provide a hull to propulsor standoff to achieve acceptable hull unsteady pressures as well as clearance for pod azimuthing. The duct diameter and thickness should also be minimized resulting in a short duct length to minimize drag, maximize efficiency, and reduce maneuver resistance of the pod. The duct diameter is driven by the rotor and stator blade design, while the duct thickness is driven by the motor design.

Scale Model Hydrodynamic Test Results Summary And Conclusions

A complete series of model scale hydrodynamic performance tests were conducted on a small-scale model of the CRDP. These tests included measurements of the open water and behind hull powering performance in the Hamburg Ship Model Basin (HSVA) tow tank and cavitation inception, torque breakdown due to cavitation and hull pressure fluctuation measurements in the HSVA large cavitation tunnel. The CRDP tested was a 1/25.11 scale model of a unit that was designed to operate on a typical twin screw panamax cruise ship at a power level of ~18 MW per pod. The CRDP was designed to provide improved powering (efficiency), cavitation inception and hull pressure fluctuation performance compared to that of a comparable power and size hub-drive pod with an open propeller. In addition, the CRDP was designed to have acceptable cavitation breakdown performance and experience no cavitation erosion during operation.

Conclusions of the test program conducted at HSVA are summarized [1] as:

(1) At $1/25^{th}$ model scale the open water efficiency at the design advance coefficient of the CRDP is η_o = 67.2% and of the comparative hub-drive pod is η_o = 64.3% [2], representing a relative improvement of 4.5% for the CRDP ({67.2/64.3}-1).

(2) Scaling model results to full-scale, the open water efficiency at the CRDP design advance ratio is η_o = 71.7%, and the peak open water efficiency is η_o = 72.1%. Applying the same scaling methods to a particular hub-drive pod yielded consistent results with previous full-scale efficiencies, and showed the CRDP relative improvement at the peak efficiency point to increase further, to about 6%.

(3) The efficiency versus advance coefficient dependence of the CRDP (Figure 6 of [1]) shows much less sensitivity to off design operation (variation in blade loading) at model scale than with the comparative hub-drive pod; i.e., even larger improvements in the CRDP efficiency at off-design conditions. Efficiency curves at full-scale cannot be shown due to business sensitivities, but the sensitivity difference between the CRDP and hub-drive pod are even more pronounced at full-scale.

(4) The improved behind hull efficiency (η_D) of the CRDP results in the use of less power for given ship speed or increased speed for given power.

(5) The CRDP as designed exhibited cavitation-free operation at full-scale up to a a cavitation index (σ) of 2.55 at a 0^{o} angle of incidence and 2.95 at an 8^{o} angle of incidence. The small amount and types of cavitation, exhibited above incidence speed by the CRDP and their stable nature led HSVA to state that no cavitation erosion would occur on the CRDP at or below the maximum speed, angle of incidence and blade loading tested. The maximum speed tested exceeded 26 knots, maximum angle of incidence tested was 8^{o} at 26 knots, and a test at 24 knots straight ahead with a 15% blade overload also met the cavitation erosion free criteria. The tests

did not go to high enough speed or loading to predict when erosion would occur, so the limits of the specific design tested are unknown.

(6) The hull pressure fluctuations induced by the CRDP have extremely low amplitudes, in fact the lowest ever seen by HSVA or Deltamarin at the clearances tested. CRDP maximum level at blade rate was 0.25 kPa at 26 knots and 24 knots with a 15% blade overload, even at 8^o angle of incidence, compared to ~1.4 kPa at blade rate at 24 knots at 0^o angle of incidence for a good comparative hub-drive pod. And those CRDP levels showed only a gradual increase throughout the speed range tested, thus supporting that continuous operation at higher speeds is viable for the specific pod designed (i.e., that specific CRDP could potentially be applied to a lower resistance, higher speed platform).

(7) The hull pressure fluctuations induced by the CRDP at higher harmonics, i.e., 3 times, 4 times, and 5 times blade rate, have extremely low amplitudes; less than or equal to 0.09 kPa at 24 knots for 0^o and 8^o angle of incidence.

(8) Torque (or thrust) breakdown due to cavitation occurred at about 26 knots with the hull tested, well above the maximum operating speed for the ship hull tested of 24.5 knots. But the falloff rate, after breakdown is very gradual, thus supporting that continuous operation above the breakdown point is viable, but with a slight impact on efficiency. By contrast, open propellers, such as those of hub-drive pods, typically experience a very rapid fall-off to near zero from the breakdown point.

Benefits Assessment Basis

The following assessment identifies key aspects of the CRDP that are considered potentially the most attractive to the commercial market. Most of these benefits are a direct outcome of and supported by the CRDP hydrodynamic demonstration effort performed at HSVA. This assessment combines that knowledge with insight gained by market research and with additional CRDP design knowledge (e.g., motor efficiency, cooling).

This effort involved market research including discussions with knowledgeable commercial ship and propulsion machinery designers, builders, testers and owners. Other efforts included gathering reports and papers, technical research, attending presentations and symposia, etc., covering numerous types of platforms and propulsion systems. From that research and an expanding knowledge base of the physical and performance features of EB's CRDP in a number of configurations, assessments of the potential benefits and detractions of the CRDP vs. currently available hub-drive pods in various platforms was accomplished. Since new commercial propulsion system advances are continuing, this effort also continues.

SIZE AND RATINGS

The initial assessment point is a comparison of the CRDP's size and rating compared to hub-drive pods capable or near-capable of delivering the same thrust; Table 1 provides that comparison. Table 1 was compiled from open literature for the hub-drive pods, with the pod ratings also based on open literature which identifies those ratings to panamax cruise ships.

EFFICIENCY AND ASSOCIATED SAVINGS

Hydrodynamic Efficiency

The maximum speeds for panamax cruise ships have also appeared in open literature, with the maximum of any today being ~25.5 kts. Based on that maximum speed and the 20MW HDP ratings above, a maximum powering point can be compared to the predicted maximum powering point for the CRDP on a panamax cruise ship derived from self propulsion testing [1]. That powering point shows the CRDP to have a ~7% efficiency advantage, or ~2.6MW lower power comsumption. A powering curve based on that 7% advantage at all speeds is considered reasonably representative of the sea trial powering performance of

Table 1- Comparison of CRDP to Commercial Pods @ Approx. Comparable Behind-Hull Unit Thrust

	ABB Azipod [2]	**Mermaid** [2]	**Dolphin** [4]	**SSP** [5]	**EB's CRDP**
Nominal Power Rating	~20MW	~20MW	~19MW	20MW	18.5MW (nominal)
Continuous Torque Rating	~1340kN-m(est)	~1250kN-m(est)	~1396kN-m	1470kN-m(est)	1918kN-m*
Length	11.40 m	11.15 m	13.05 m	11 m	**3.90** m
Hub diameter	2.85 m	2.90 m	~2.8m±.2 (est)	~2.9m±.2 (est)	1.46 m
Propeller diameter	5.80 m	5.75 m	6.0m	6.25 m	4.9m (propeller) 5.85 m (duct)

*The CRDP continuous torque rating includes a minimum of 30% margin on pullout; that margin is therefore available for temporary maneuvering loads.

today's best at-sea hub-drive pods on a panamax cruise ship hull form. That powering curve is shown in Figure 1 below alongside the CRDP powering curve from testing at HSVA [1]. Alternatively, at the same power level the ship can be propelled at higher speeds with the CRDP than with the comparative hub-drive pod, an ~.4 knots higher speed than the hub-drive pod at the CRDP continuous torque rating.

Motor Efficiency

Besides the hydrodynamic efficiency advantage demonstrated by model testing, the CRDP could also provide a significant motor efficiency advantage. Wound field synchronous (WFS) motors power most current hub-drive pods. The CRDP is powered by a permanent magnet (PM) radial field motor, which has a clear efficiency advantage over WFS motors since power does not have to be applied to the field (rotor), and field power losses are thus eliminated. Figure 2 below shows the efficiency of the PM motor (blue) for the 18MW CRDP vs. a typical WFS motor (red), plotted vs. ship speed. At full power the PM motor is about 2% more efficient (PM = 98.8%), but the PM motor efficiency advantages are most dramatic at lower power levels, approaching a 50% improvement at 4 knots. Figure 2 also shows the combined efficiency advantage from the 18MW PM motor and CRDP hydrodynamic performance, and the resulting power savings vs. ship speed, with the power savings scale to the right of this plot. Taking this projection one step further, Figure 3 shows revised ship powering curves which now include the effect of the PM vs. WFS motor efficiency advantage. It is noted that these efficiency comparisons do not take into account novel drive schemes that may allow these motors to be driven more efficiently at lower power. For instance, drive technology exists that can power part of the windings (e.g., reduced phases), thus reducing winding losses at part loads, but these can be applied to both motor types. The efficiency difference might therefore be reduced at loads lower than 50%, but the CRDP motor would still be more efficient than the WFS with the same type of drive. However, there are other factors that bias this comparison in favor of the hub-drive pod as discussed below, so the overall comparison is considered reasonable.

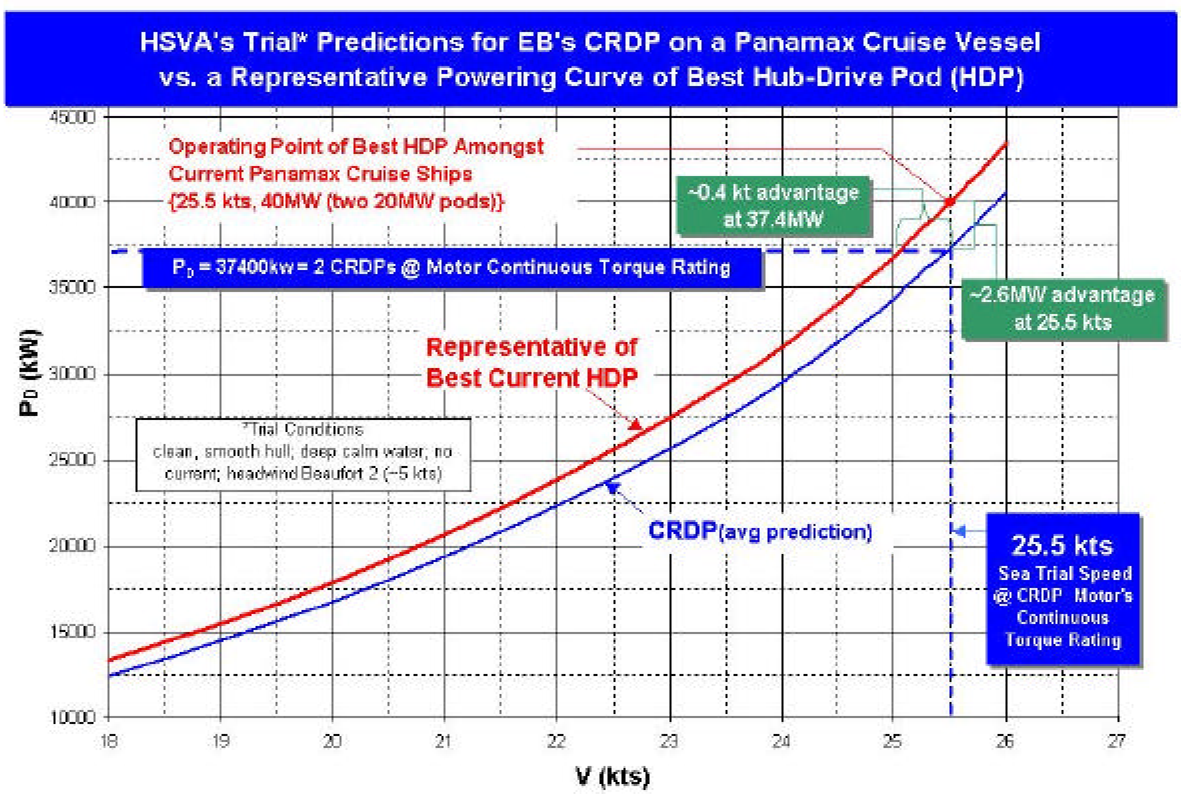

Figure 1 Behind Hull Powering Results, CRDP vs. Good Representative Hub-Drive Pod

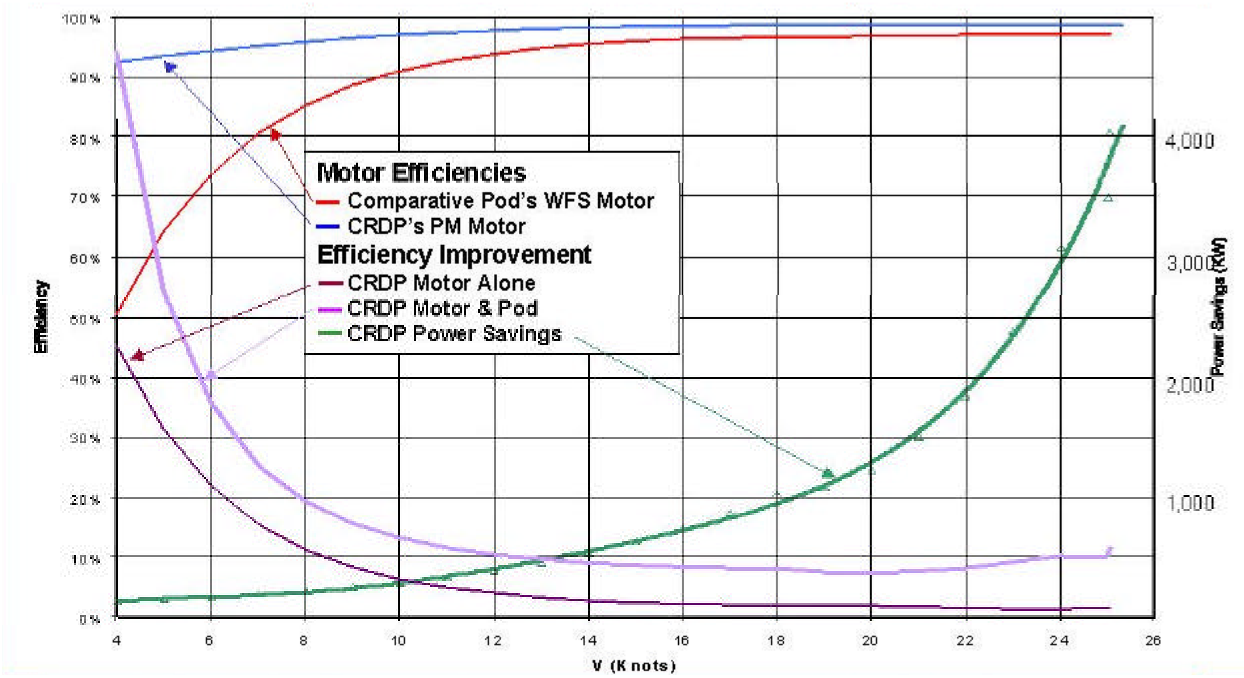

Figure 2 CRDP w/PM Motor Efficiency vs. Conventional Hub Drive and WFS Motor

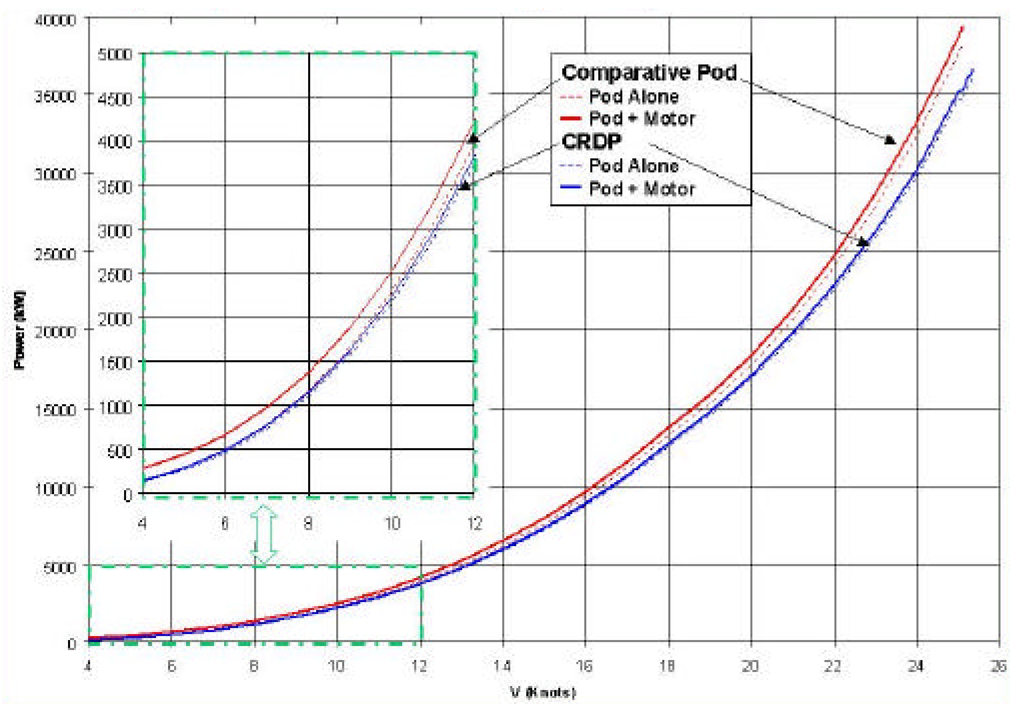

Figure 3 Behind Hull Powering Curve, CRDP vs. Comparative Hub-Drive Pod with Both Hydrodynamic and Predicted PM vs. Expected WFS Motor Efficiency Accounted for

Potential Annual Savings

Figure 4 below takes this efficiency comparison even further, by showing a potential annual power/cost savings for the CRDP in a panamax ship. This projection was developed from an average annual operating profile of several panamax ships from data provided by Deltamarin and projecting the powering difference of the CRDP hydrodynamic and motor performance vs. a conventional hub-drive pod with WFS motor from Figure 3. Note that for ~40% of the annual hours the ship is at standstill. The power generating cost and efficiency, \$0.10/kW-hr and 95%

drive efficiency, have been used in other commercial marine papers and appear reasonable by comparison to other more complex estimating methods evaluated.

Projected Efficiency Gains Are Conservative

Some factors not accounted for in this savings projection that bias the results in favor of the hub-drive pod, and thus bring some degree of conservatism to this projection are:

Projections Are Based on Sea Trial Conditions, Resulting in Lower Than Average Power Requirement

The powering projections at all speeds, as shown in Figures 2, 3, and 4 are for straight ahead, sea trial conditions (clean smooth hull, deep calm water, no current, 2.365m/sec headwind (Beaufort 2, ~5kts)). These are not representative of even average conditions over the life of these ships, which include operating at the following conditions:

- Deepwater conditions: Trim, wind, current, waves and hull fouling are factors having significant impact on ship resistance. A +15% loading factor is considered a normal adjustment from sea trial to average deep-water conditions. In heavy weather the overload condition can easily be 50%.
- Shallow water conditions: Water depth also has extremely strong influence on resistance. In one report it was noted that that for panamax size cruise ships (~8m draft) strong depth impact starts around 30m water depth and in 15m deep water these vessels can typically only reach 50% of top speed.
- Low speed operation: At lower speeds in particular, sea trial conditions are the most unrepresentative, since lower speed ranges are likely in shallow depth, high harbor maneuvering conditions where propeller loading would be considerably increased. And in those maneuvering conditions the pods are usually turned into a "crabbing" orientation, in which they are typically oriented between 30 to 90 degrees to each other to allow rapid thrust vectoring (e.g., see Figure 5). The 4 to 12 knot powering portion of the Figure 4 powering comparison is based on both pods powering from the 0^o angle of incidence position; the crabbing position changes this. Thus higher blade loads will be experienced during low speed operation than has been analyzed, and those operations will be at inflow angles of incidence to the pod, both factors increasing the advantage of the CRDP.

CRDP Operation at These More Severe Operating Conditions Will Be Even More Efficient

The CRDP's higher efficiency and flatter efficiency vs. speed of advance curve as shown in Figure 6 below (Figure 6 of [1]) demonstrates that the CRDP will perform even more efficiently at higher, more normal loading conditions (lower advance coefficient, J) and result in additional savings. This figure shows model

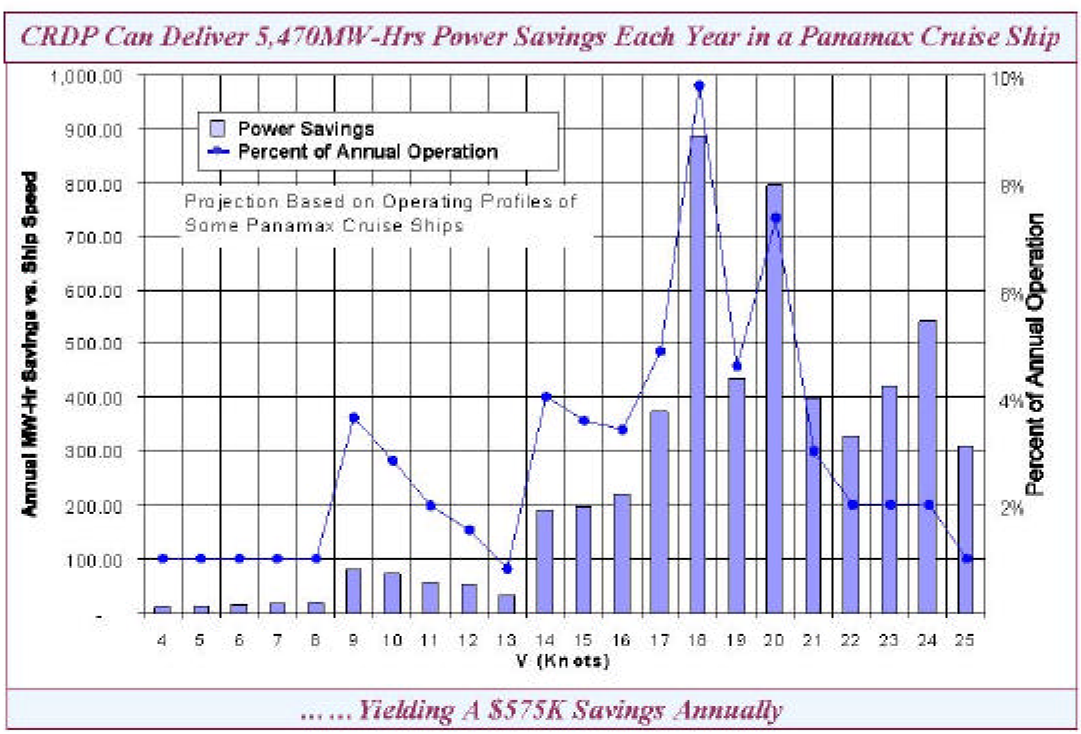

Figure 4 Potential CRDP Annual Fuel Savings for Representative Panamax Cruise Ship

scale open water efficiency (η_o) versus advance coefficient for the CRDP and a good comparative hub-drive pod. As shown, at the peak efficiency advance coefficient (J/J_{Peak} = 1), the CRDP shows ~4.5% higher efficiency at model scale compared to the representative hub-drive pod. But in addition, at off peak advance coefficients the CRDP efficiency is shown to be much less sensitive than that of the comparative hub-drive pod. As an example (from [1]), if the off design operation is limited to a 3% drop in efficiency from the HDP peak (to about 61.3%), the off design operation range of the CRDP is almost twice that of the hub- drive pod range (.54/.28 = 1.93). This insensitivity of the CRDP to off design operation can enable lower ship operating costs and higher operating speeds in heavier sea states with the CRDP. In addition, it allows the design and use of fewer CRDP units for operation over a range of power levels than possible with hub-drive pods. And while impressive at model scale the difference is even more at full-scale, although it cannot be presented due to business sensitivities.

Thus using sea trial conditions is conservative in the annual powering projections of Figures 3 and 4.

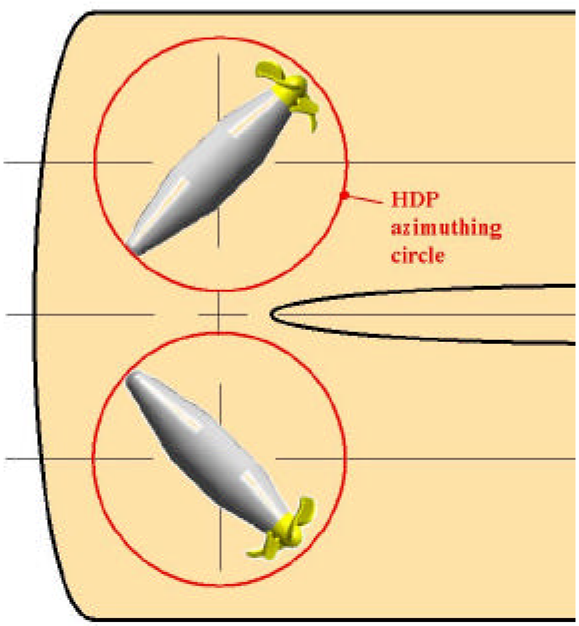

Figure 5 Typical Pod Crabbing Orientation for Harbor Maneuvering

Additional CRDP System Efficiencies Are Not Accounted For

- Additional electrical system power savings. The CRDP's PM motor operates at a higher power factor (~.94) than does a WFS motor (~.72 to .82); that difference can amount to a ~ 1% higher efficiency of the generator and distribution system.
- Less secondary system power consumption.
  - The CRDP does not require a dedicated cooling system, and therefore the energy to run such a system is saved (See "Secondary Ship Design Impacts/Opportunities" discussion on page 10).
  - The CRDP also uses seawater lubricated bearings instead of lubricated oil bearings. The ship's lubrication systems energy consumption is thus also reduced.

These differences are also not accounted for in Figures 3 or 4, thus further adding to their conservatism.

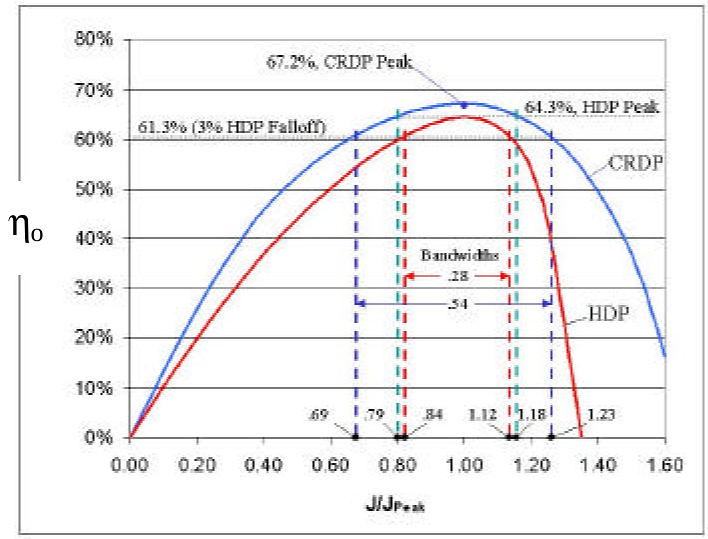

Figure 6 Open Water Efficiency at Model Scale of a CRDP Developed for a Panamax Cruise Ship vs. a Representative, Good Hub-Drive Pod

SHIP DESIGN OPPORTUNITIES

The CRDP could offer more freedom to the ship designer; in certain circumstances this may be a significant advantage.

Narrower Ship Beams, And Unique Configurations:

The pod size itself offers an obvious benefit for narrow beam ships, evident by the length comparison of Table 1 and also depicted in Figures 7 and 8. But beyond the conventional twin screw ships as tested the CRDP size can also support more unique configurations that conventional hub-drive pods cannot, or can support them in more flexible arrangements.

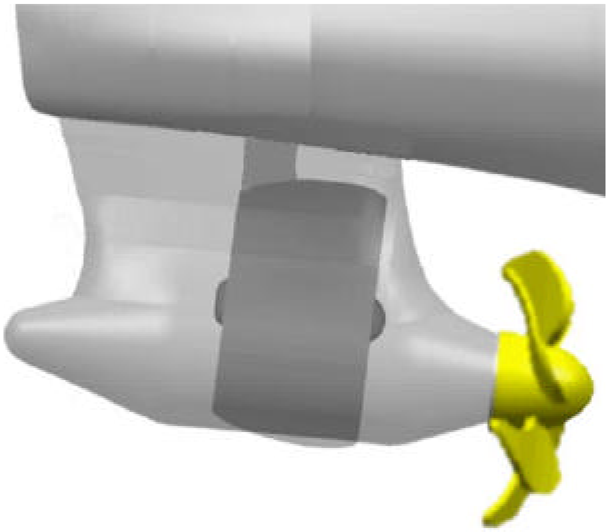

Figure 7 Typical ~20MW Commercial Pod vs. ~18.5MWCRDP Shown in Relative Size (CRDP ~1/3 length)

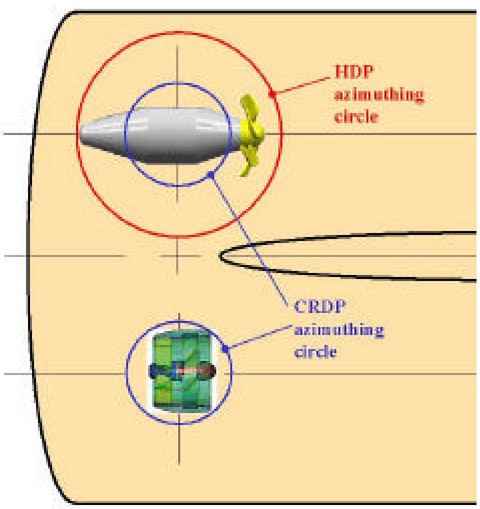

Figure 8 Typical Twin-Screw Panamax Cruise Ship - Hub-Drive Pod vs. CRDP Arrangement Comparison

- Consider, for instance, a three-pod arrangement similar to the “Voyager of the Seas” Class (Figure 9). Those ships have two azimuthing “pulling” pods (facing forwards) and one fixed pushing pod, with the pod size (power) and spacing between pods dictated by the azimuthing pods turning circle. The CRDP, being shorter in length, could support a two-pod arrangement delivering comparable thrust, or a three across, all pods azimuthing configuration, if desirable to the ship designer or owner (Figure 10). It could also support more pod arrangements than the hub-drive pods, which might be of advantage for locating pods in more ideal wake locations and thus further improve hull efficiency (η_H) or cavitation performance as desired.

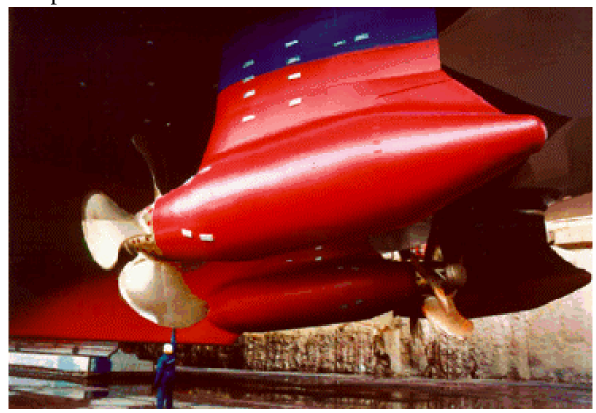

Figure 9 Three 14MW Pod Arrangement on Voyager of the Seas

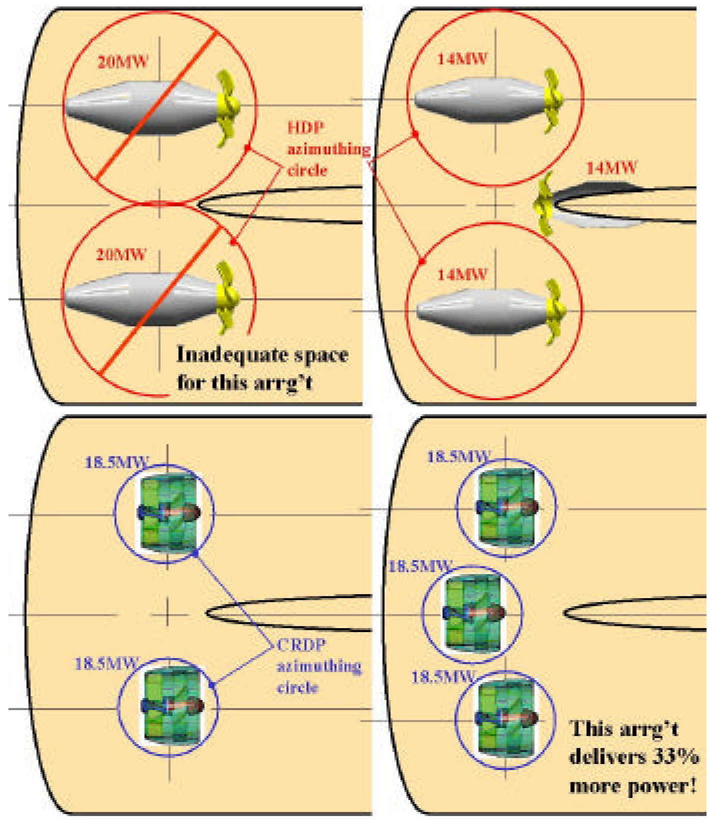

Figure 10 HDP vs. CRDP in Narrow Ship Beam Arrangements

- In the case of a four pod ship, such as the Queen Mary 2 (as noted in reference [3]), the CRDP could obviously support more pod arrangement opportunities than a conventional hub-drive pod. The 4 hub-drive pod arrangement for the Queen Mary 2 will include two azimuthing and two fixed pods. A more flexible arrangement, if desired, with all azimuthing pods can easily be imagined with the CRDP, given the significantly smaller pod size. But also of note in reference [3] is a statement that the four-pod configuration was selected after a three-pod configuration was evaluated (26.5MW each); the three-pod configuration was abandoned due to excess per pod weight, in excess of 300 tonnes. Since the CRDP also offers a weight advantage it carries a lower probability of creating a trim problem for the ship, allowing for a more rationale distribution of the machinery and load items, and it might thus support a three-pod configuration where the hub-drive could not.

- Also consider a booster pod arrangement, such as the Costa Classica extension project. The smaller CRDP length can allow the pod to be located further behind the center skeg, due to the smaller pod turning circle. The ship designer would have to determine whether there was any advantage on a particular ship, but with that freedom it might allow internal arrangement improvements or result in higher efficiency and ship speed because of a more favorable wake in that position. Another opportunity for the designer would be putting in a more powerful azimuthing pod in the same space.

More Freedom In Stern Configuration:

The CRDP also offers opportunities to reconfigure the stern lines, which could enable increased payload, increased hull efficiency (and further reduce operating costs), or podded propulsion of Ro-Ro platforms where conventional hub-drive pods aren't feasible.

Two CRDP Features Enable These Design Opportunities:

- Lower Vibration Levels.

  The CRDP pressure fluctuation amplitudes are smaller than hub-drive pods, which may allow reduced clearance between the pod and hull.

  Hull clearance (clearance between propeller blade tips to nearest point of hull) is typically set by propeller cavitation effects, and in particular hull vibration associated with cavitation. The propeller operates in a flow field affected by the hull, which is decelerated and non-uniform into the propeller, and has negative effects on propeller operation. The propeller induces an unsteady pressure field that affects the submerged part of the stern, mainly caused by cavitation. This unsteady cavitation is often the main cause of ship vibration problems [2]. The vibration tolerance level varies dependent on the type of ship. As a rule of thumb, cruise liners and cruise ferries are typically designed to achieve pressure amplitudes on the hull of less than 2kPa at blade rate. By comparison fast ferries would typically allow 3 to 3.5kPa, container ships with installed propulsion power in the range of 20 to 30MW would typically allow 3 to 5kPa and tankers would typically allow 5 to 6kPa. Clearance for a cruise ship has typically been 25% to 35% of the propeller tip diameter to achieve its vibration tolerance level; other ship types would of course have different typical clearances. The tip (or hull) clearance both provides distance to dissipate energy from the source (propeller cavitation) as well as placing the propeller in a more benign wake and thus limiting cavitation.

  In the CRDP configuration tested, with roughly comparable hull clearance (CRDP duct outside diameter and clearance ≈ hub-drive pod blade tip outside diameter and clearance), pressure fluctuation levels are so dramatically lower than conventional pods that the CRDP clearance to the ship could be reduced. CRDP levels are less than 20% of the hub-drive pod levels as noted in reference [1] and page 3, paragraph (7) herein. Note also that the CRDP levels are ~10% of the "normal tolerance level" of 2kPa for a cruise ship, even at an 8^{o} angle of incidence. Besides showing dramatically lower levels these results also show less sensitivity to wake than do hub-drive pods, further supporting the tolerance to smaller hull clearances.

- Pod Configuration

  The CRDP 18MW design for this demonstration was developed with a self imposed specification on duct diameter and clearance ≈ propeller diameter and blade tip clearance of the comparable hub-drive pod. But the CRDP could be redesigned with a smaller duct diameter if desired. Although the impact would be a reduction in efficiency and lengthening of the CRDP both those features have significant margin to trade off vs. the comparable hub-drive pod. And efficiency, although affected by a reduced diameter would not be impacted as much as would a conventional hub-drive pod if reduced by the same amount.

Resultant Stern Configuration Opportunities

- The stern could be lowered thus allowing more gentle ship lines.
  - Thus providing a more gentle distribution of displacement, reducing the boundary layer thickness and steady pressure gradient. Consequently this could reduce ship drag and thereby improve behind hull efficiency (η_D). This gain might be great enough to offset reduced pod efficiency in the case of applying a smaller diameter CRDP in order to lower the stern.

- More gentle ship lines could create more aft payload space.

- Ro-Ro ships must work the requirement to roll cargo on and off the ship around the draft and internal height constraints for the propulsion and azimuthing system. In the case of an azimuthing podded propulsion system the azimuthing system imposes a height requirement directly above the propeller that non-podded ships do not have. This has been a reason for disqualifying podded propulsion in some Ro-Ro designs. The reduced hull clearances and/or smaller propeller/duct diameters enabled by the CRDP might thus enable more extensive podded propulsion on Ro-Ro ships, by allowing deeper stern lines and thus lowering the internal height constraint.

More Payload

As noted above, the CRDP allows stern configuration opportunities that may open up additional space for payload. But by virtue of the CRDP's improved efficiency it can also offer additional payload opportunities by allowing fuel bunker reductions while still supporting the same service/refueling range.

Secondary Ship Design Impacts/Opportunities

- The CRDP motor does not require a dedicated cooling system, therefore there is less cooling system demand resulting in secondary efficiency savings and cooling system equipment reduction. The CRDP features allowing the elimination of the cooling system are:
  - The CRDP rotor, being a properly designed PM machine, generates little losses.
  - The CRDP stator, being located in the duct, is cooled by the seawater passing by the hull, both internal and external of the duct.
    - The surface area of the duct immediately surrounding the motor, being much greater and more uniformly exposed to the passing flow than the comparable surface of a hub-drive pod motor, enables this cooling method.
    - Also, the CRDP motor stator core length is considerably shorter than a comparable hub-drive pod, since the stator core diameter is considerably greater than the hub-drive pod's. The shorter core length shortens the conduction path from the center of the core to the end-turns, enabling more uniform temperatures throughout the CRDP stator.
- Lower power demands due to higher CRDP efficiency can support lowering power plant space, weight and cost.
- Passenger comfort at higher speeds/higher seas. The low pressure fluctuation levels demonstrated by the CRDP both straight ahead at high course keeping angles of attack could allow vessels to operate at higher speeds or fill more spaces aft with passengers without a reduction in their comfort level.

SHIP OPERATION OPPORTUNITIES

Higher performance in all operating conditions

As previously noted, the CRDP's higher efficiency and flatter efficiency vs. speed of advance curve, as shown in Figure 5, demonstrates that the CRDP will perform more effectively and efficiently at all loading conditions. A maximum continuous thrust vs. ship speed analysis for the tested panamax hull was performed. The analysis assumed the CRDP and the hub-drive sea trial powering curves of Figure 1 as a starting point. Based on that starting point the maximum continuous powering/thrust capability at each ship speed is based on the motor continuous torque ratings (Table 1) and open water performance curves for each pod (e.g., Figure 5 of [1] and Figure (6) of [2]). The advance coefficient (J), was varied until the torque coefficienct (K_Q) of each pod produced the maximum continuous torque; the thrust coefficient (K_T) was then determined and used to calculate the thrust.

Figure 11 below shows some of the sea trial and maximum thrust operating points on the CRDP and hub-drive pod open water efficiency curves. At the sea trial operating points for each pod they are delivering equivalent thrust, at the maximum continuous thrust points they are both operating at the motor continuous torque point. In addition, operating points are shown for the CRDP which match the hub-drive pod's maximum continuous thrust point, thereby enabling comparison of efficiency at the same thrust.

By comparing the sea trial operating points it should be noted that the hub-drive pod was given a slight additional advantage in this analysis since its sea trial starting point is at a more favorable point than the CRDP's for all ship speeds. The hub-drive pod's sea trial point is just past its peak efficiency point whereas the CRDP's is just before that point. For thrust and blade loading to increase, propeller speed must also increase, and J therefore decreases. From Figure 11 it can be seen that efficiency will therefore initially increase from the sea trial condition as J decreases for the hub-drive pod whereas efficiency will only decrease as J decreases for the CRDP. Thus the relative efficiency and maximum thrust benefit predictions for the CRDP thus computed should be conservative at all thrust conditions and all ship speeds.

The analysis showed the CRDP relative hydrodynamic efficiency advantage growing to over 10% at 13 knots and over 13% at 10 knots when matching maximum thrust capability of the representative hub-drive pod at those speeds. Or, the CRDP can produce steadily greater thrust than the hub-drive pod, 2.5% additional at 24 knots but increasing to 20% additional thrust at 10 knots, thus enabling higher ship speeds in heavier seastates, casualty conditions, etc. In addition, cavitation and pressure fluctuation testing has demonstrated that the higher CRDP efficiency performance also comes with improved cavitation performance over a broader range of blade loading as well.

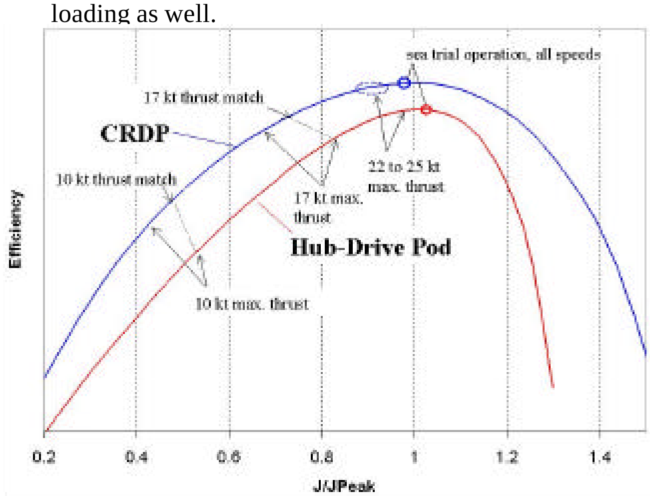

Figure 11 CRDP vs. Hub-Drive Pod, Operating Points on Open Water Performance Curve Predicted for Sea Trial and Maximum Thrust Conditions

Less Maintenance

The CRDP is expected to require significantly less maintenance than other pods for a number of reasons as listed below:

- Less cavitation erosion can be expected, therefore resulting in lower maintenance costs. Besides the cavitation testing that supports this conclusion is one design difference of note: the strut position relative to the propeller's swirling discharge. In the case of hub-drive pods, usually 1/3 to 1/2 the strut is exposed to the strong propeller discharge, and there have been reports that this exposed area is highly susceptible to cavitation erosion as well as vibration excitation. The CRDP strut on the other hand is entirely outside and protected from the propeller discharge and should not experience comparable erosion or vibration. CRDP stator vane erosion (stationary blades) might be of concern since they are exposed to propeller discharge, but these vanes are designed as a matched set with the rotor blades to minimize cavitation erosion amongst other factors.
- Bearings. The CRDP uses seawater lubricated journal and thrust bearings, thus avoiding the necessity for seals to protect oil filled bearing cavities. This type of bearings has been used for many years and while successful they have evolved from yesteryear's brass backed rubber stave bearings to special polymer materials today that improve bearing life and reduce friction. The CRDP journal bearing is designed within industry standard design guidelines for projected area pressure loading. The thrust bearing is designed to operate at higher pressure than that calculated for the journal bearing projected area pressure. The thrust bearing is designed to operate at approximately the peak calculated journal bearing pressure, which is approximately six times the projected area pressure. The thrust bearing design was tested and verified using a scale model bearing approximately 1/3rd the diameter of the CRDP thrust bearing at maximum CRDP surface speed and pressure. The thrust bearing design demonstrated little or no wear while operating at maximum CRDP conditions with a friction coefficient of 0.005. The expected maintenance interval of both the CRDP journal and thrust bearings is at least 12 years.

  Current commercial propulsion pods by contrast do not appear to either incorporate a robust bearing service life or separate bearing cavity seals to prevent seawater contamination of the lubrication system. The typical commercial pod uses oil-lubricated roller bearings for both the shaft radial and thrust bearings, which have become a maintenance problem for many ship operators, requiring expensive dry-dock periods to disassemble the pod(s) and replace roller bearings. The current bearing problems appear to be aggravated by early seal failures, in some reported instances at least, that introduce seawater into the bearing cavity and lead to rapid bearing failure. Also, the failed seals and flooded bearing cavities can allow oil to escape the pods and become penalizing environmental spills.
- Cooling System: Less cooling system equipment is required since the CRDP is totally cooled by naturally passing seawater past the duct and by the pressure developed by the propeller rotor causing seawater flow through the gap between the motor stator and rotor. This feature also lowers overall system noise levels by eliminating disturbing noises emitting from cooling fans, etc., which are required for most other pods.
- Lubrication System: Separate bearing lubrication system is avoided, since the bearings are seawater lubricated.

Higher Attainable Ship Speeds

From information gathered, the greatest apparent obstacle to achieving higher ship speeds with current commercial hub-drive pods is primarily due to high cavitation and pressure fluctuation levels, aggravated by pod dithering in high speed course keeping and by potential for strong propeller/strut vibration and erosion effects (as also noted in the "less maintenance" discussion above). The CRDP's demonstrated performance on this initial pod demonstrator, which by the way was not designed to achieve higher speed than the maximum speed identified for the particular panamax cruise ship, was dramatically better than the comparative hub-drive pod.

Higher performance in single pod operation. Many pod propelled cruise ships have had publicized propulsion system problems. Other podded ships, particularly other ship types, may have also experienced problems but have not been as widely publicized. Some of these casualties were known to involve at least one pod, and others, while not necessarily caused by the pod, may have still disabled powering one pod. Some of these resulted in cruise cancellation in mid-cruise with considerable revenue impact. It is reasonable to assume several of these resulted in single pod operation to either complete the cruise or get back to port. Infinity and Summit in fact were noted to have operated in single pod mode at lower ship speeds and modified itineraries in order to support scheduled cruises while awaiting a time window for repairs. It is therefore realistic to consider this operating mode as being of some interest to a commercial ship owner/operator. As already noted the CRDP can deliver more thrust at somewhat higher blade loading than the hub-drive pods and therefore will support higher speeds in these casualty conditions.

CONCLUSIONS

In comparison to currently available commercial hub-drive pods:

- CRDP delivers required net thrust with a smaller pod (~1/3 as long).
- CRDP is more efficient in all operating conditions (e.g., sea trial condition, fouled hull, maneuvering, and varying sea states) than current hub-drive pods. Overall efficiency advantage is a result of hydrodynamic, motor and secondary system efficiency advantages.
- CRDP is less prone than hub-drive pods to performance degradation, both straight ahead and at steering angles.
- CRDP provides better passenger comfort; ~5 times lower hull unsteady pressure levels for given hull clearance will result in reduced hull vibrations.
- CRDP can achieve higher ship speeds with acceptable cavitation and no risk of cavitation erosion.
- CRDP allows more hull design flexibility (narrower ship beams, reduced clearance to hull, more gentle and fuller stern lines, etc.).
- CRDP can support a wider range of operating modes, such as single pod propulsion on multi-screw ships, than conventional hub-drive pods.
- CRDP allows use of an alternate water lubricated bearing system that does not require lubricating oil or seals and is expected to be more reliable than the current practice of oil lubricated roller bearings.
- CRDP is expected to require less maintenance. The maintenance advantage results from reduced cavitation erosion, reduced support system equipment (e.g., reduced cooling and lubricating system requirements) and the alternate bearing system noted above.

The CRDP, therefore, should be a more economical choice for a wider range of ship types than other propulsion alternatives.

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NOMENCLATURE

ARL	The Pennsylvania State University Applied Research Laboratory	
CRDP	commercial rim–drive propulsor pod, patents pending	
D_R	rotor diameter	
EB	Electric Boat Corporation, a General Dynamics Company	
HSVA	Hamburg Ship Model Basin (Hamburgische Schiffbau-Versuchsanstalt GmbH)	
ITTC	International Towing Tank Conference	
J	advance ratio or coefficient	$= V/n \bullet D_R$
K_T	thrust coefficient	$= T/\rho \bullet n^2 \bullet D_R$
K_Q	torque coefficient	$= Q/\rho \bullet n^2 \bullet D_R^5$

L	length	
MW	megawatt	
n	rotor rotational speed, in revolutions per second	
Q	steady torque	
$\mathbf{P_D}$	Power delivered to propeller	$= 2 \bullet \pi \bullet n \bullet Q$
$\mathbf{P_E}$	Effective Power delivered by propeller pod	$= R_T \bullet V$
$\mathbf{R_T}$	Total Ship Resistance	
RPM	revolutions per minute	
T	steady thrust	
t	thrust-deduction fraction	$= (T-R_T)/T$
V	ship speed	
$\mathbf{V_A}$	speed of advance of propeller	$= V \bullet (1-w)$
$\mathbf{V_{Rel}}$	relative velocity	
w	Taylor wake fraction	$= (V-V_A)/V$
h_O	complete pod efficiency in open water $= (J \bullet K_T)/(2 \bullet \pi \bullet K_Q)$	
h_D	propulsive efficiency (a.k.a., quasi-propulsive coefficient) $= P_E/P_D = \eta_R \bullet \eta_O \bullet \eta_H$	
h_H	hull efficiency	$= (1-t)/(1-w)$
h_R	relative rotative efficiency $= K_{Q\ (open\ water\ test)} / K_{Q\ (propulsion\ test)}$	
n	water kinematic viscosity	
r	water mass density	
s_o	cavitation index (related to ship speed) $= (p_o-p_v)/(0.5\rho \bullet (V_A)^2)$	
•	multiplication sign	

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