CRP Azipod® for Ultra Large Container Ships-
An Advanced Cost-Effective Solution

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Abstract

In this paper, propulsion system dimensioning and operational benefits of the CRP Azipod® propulsion system for 12000 TEU ULCSs are presented. System dimensioning is based on the data received from model tests conducted at the Samsung Ship Model Basin in South Korea. The CRP Azipod® propulsion system was shown to have the best hydrodynamic as well as total propulsion efficiency when CRP, twin-screw twin-skeg and single-screw systems were compared in model tests. Dimensioning of the CRP system is presented in detail and differences compared with the twin-screw system are considered. Finally, an operation cost comparison between CRP, twin-screw twin-skeg and single-screw systems for 12000 TEU ULCSs is presented. The CRP Azipod® system is clearly the best propulsion system for ULCSs when operation costs are considered.

Introduction

Due to continuous growth in world trade transportation needs are growing. This means container transport will increase. Despite recession facing the global economy at the present time, also influencing container transportation markets [1], container transport is expected to grow faster than world trade in the long run, ie. container transport will have an increasingly larger share of the total global transportation market. It has been observed based on container volume growth during the past twenty years, that we should expect a doubling in container volume on most major routes in less than ten years [2].

One future trend in the container business is that the top 20 carriers will have an increasing share of global slots. This means that the size of ships will be larger. With increasing container carrying capability per vessel, transportation cost per container will go down making it even more economical to transport by container vessel. This will further increase container transport.

Building 9000, 12000 or 15000 TEU vessels using existing technical solutions for propulsion machinery is problematic. The largest slow-speed engine built today has 68 000 kW (95 000 BHP). This is insufficient if the target is 9000, 12000 or 15000 TEU carriers having speeds up to 25.5 knots, because the power requirement of these vessels run up to 100 MW (136 000 BHP).
Solutions discussed for these future vessels thus far have included building larger slow-speed engines by adding more cylinders in single-engine single-screw system or having two slow-speed engines in a twin-skeg hull in twin-engine twin-screw system. Other possible solutions mentioned in different publications have been contra-rotating propellers in single shaftline and single-engine twin-pod systems.

Some slow-speed engine manufacturers have already planned to build new larger engines with 14, 15 or even 18 cylinders. However, delivery of 80 000-90 000 kW (108 800 BHP-122 400 BHP) using only one propeller can be problematic due to difficulties in propeller manufacturing and the effects of increased propeller diameter on propeller tip speed.

It is also possible to have two coexisting slow-speed engines and two propellers in a twin-skeg hull. This type of vessel is very expensive and demanding from the ship building point of view. Another drawback is the low hydrodynamic efficiency which causes a greater demand for installed propulsion power.

The optimum propulsion system solution for in ultra large container ships is to use CRP Azipod® propulsion. The CRP system combines well-proven slow-speed engines and Azipod units. It can be implemented with existing slow-speed engines, propellers and Azipod units and demonstrates clearly the best hydrodynamic efficiency of all options for ULCSs.

**CRP Azipod® Propulsion System**

The CRP Azipod propulsion system consists of two contra-rotating propellers. Located on the same axis, but without physical connection, the pulling propeller of the Azipod unit will contra-rotate in relation to the shaft-driven main propeller. There is no need for a conventional rudder because the pulling Azipod unit acts as one, figure 1. Both propellers are fed by independent power supplies which means high redundancy.

![Figure 1. CRP Azipod® Propulsion System.](image)
Due to the hydrodynamic benefit of CRP system, propulsion power requirement is lower compared with single- or twin-screw solutions. These hydrodynamic benefits have been verified in model tests conducted at Samsung Ship Model Basin in South Korea. Model test arrangements and results are discussed more thoroughly in chapter 3.

In the CRP Azipod® system the power ratio between main propeller and Azipod propeller is typically close to 70% and 30%, respectively. With this power ratio, the optimum Azipod unit size and type with respect to cost and hydrodynamic efficiency can be achieved. The optimum power ratio would be 50% for each propeller, but this would apportion exceedingly high power to the Azipod unit and thus increase electrical losses and reduce total efficiency of the whole system.

The CRP Azipod® propulsion system offers numerous technical and operational benefits:

**Technical**
- Easy mounting at the shipyard
- Two independent propulsion systems give high redundancy
- No need for stern thrusters
- Flexible general arrangement
- Less pressure pulses on vessel hull
- Easily adjustable propulsion machinery to match required propulsion power

**Operational**
- Power plant principle utilization in different operation modes
  - Diesel engine operation at optimum load
  - Better fuel economy
  - Less emissions, environmentally friendly
- Improved maneuvering
  - In ports, channels and canals, significant time savings
  - Less tug assistance in ports
  - Very good vessel operation at lower speeds
- Greater safety in extraordinary situations such as crashstop and emergency maneuvering, bypass capability

**Economical**
- Highest propulsion efficiency and therefore maximum fuel economy
- More cargo space, i.e. greater revenue
CRP Azipod® Model Tests

Model tests for different ULCS propulsion systems took place in Samsung's Samsung Ship Model Basin in South Korea [3]. CRP, twin-screw twin-skeg and single-screw systems were tested (figures 2, 3 and 4) in order to make the best possible comparison between all viable propulsion concepts for ULCSs.

![Figure 2. CRP Azipod® model.](image)

![Figure 3. Twin-screw twin-skeg model.](image)

![Figure 4. Single-screw model.](image)

The test program included resistance and self propulsion tests for all three hull variants as well as open water tests for pod and propellers. This program did not include cavitation or maneuvering tests. The sole purpose was to determine the most efficient propulsion system for this vessel type.

At 25.5 kn (NCR) with a 15 % sea margin the CRP Azipod® system delivered propulsion power was 11.4 % lower compared with twin-screw and 7 % lower compared to single-screw system.

Total efficiency for the CRP Azipod® system was 9 % better compared with twin-screw and 5 % better with single-screw system. Conventional shaftline losses were estimated to be 1.5% and electrical losses - including generators, switchboards, transformers, drive and motor - were estimated to be 8%. It has to be noted that even though electrical losses are 8 % or more than conventional shaft line losses, this 8% only applies to 30% of total propulsion power. Thus the CRP Azipod® concept is clearly the most efficient system for this size ULCS and beyond.

CRP Azipod® and Twin-Skeg Twin-Screw Propulsion System Dimensioning

Traditionally container vessels have used slow speed-engines. The dimensioning of those for propulsion purposes is well known. However, the CRP Azipod® system combines both slow-speed engines and diesel-electric propulsion. Dimensioning of the diesel-electric propulsion system is not widely known among all interested groups. There are several important dimensioning criteria, which need to be carefully considered in order to avoid, for example, overdimensioning of the Azipod unit.
As a result of machinery dimensioning, the best machinery for ULCSs should be found. Special attention in selection should focus on first cost of equipment, total cost of shipbuilding as well as operational and maintenance costs. In order to calculate first cost and sizes of the main and generator diesel engines, total diesel engine power required on board should be known. The total diesel engine power needed depends on the required propulsion and auxiliary power and the selected propulsion system.

The required propulsion power calculation must start from the amount of delivered propulsion shaft power at the ship’s service speed under sea trial conditions. Sea trial conditions mean that the ships hull is clean and newly painted, i.e. ship hull resistance, which affects required propulsion power, is at a minimum. A ship’s service speed is also a specification which ship owners buy from the shipbuilder. The only way to obtain reliable information on propulsion power requirements is to carry out model tests.

In the following two chapters twin-screw twin-skeg and CRP Azipod® system dimensionings are presented. Both chapters are self explanatory and therefore there is some repetition. The dimensioning procedure is similar for both propulsion systems but in the dimensioning itself there are differences which are pointed out.

**Twin Screw Twin Skeg System Dimensioning**

**Main Engine Dimensioning**

In the Twin-Skeg (TS) concept the propulsion system uses two 2-stroke slow speed-engines. The engines are placed in separate skegs. One slow-speed engine could be used up to the 9000 TEU vessel size. For larger vessels, there are no propellers available at this time therefore two engines must be used to obtain sufficient power. The following dimensioning procedure is also valid for the Single-Screw system. The main engine dimensioning process for the Twin-Skeg system is as follows:

**Step 1.** Define the service speed power requirement

\[ P_{\text{Service speed trial TS}} = P_{\text{Service speed trial CRP}} \times (1 + \text{Propulsion power gain %}) \]  

at sea trial conditions. Service speed power is the shaft power delivered at service speed. This value can be calculated from the known CRP service speed propulsion power by using the propulsion power gain percentage value. Propulsion power gain percentage value is the ratio of service speed power at sea trial conditions needed by the twin-screw and CRP systems. Propulsion power gain should be verified by model tests. According to model tests the power gain is 11.4%.

**Step 2.** For container ships adhering to schedules is very important in any sea condition. To ensure this, a 15-30% sea margin is typically added to the service speed power requirement in trial conditions. The sea margin is added by multiplying service speed power at trial conditions by factor \((1 + \text{Sea margin \%})\)

\[ P_{\text{Service speed TS}} = P_{\text{Service speed trial TS}} \times (1 + \text{Sea margin \%}) \]
**Step 3.** In order to calculate the required propulsion operating brake power, meaning the power needed at the diesel engine brake at service speed, we must add the shaftline losses to delivered shaft power, figure 5. Values between 1.5-3% are typically used.

\[
P_{\text{Operating power TS}} = \frac{P_{\text{Service speed TS}}}{(1-\text{Shaft losses } \%)}
\]  

(3)

Propulsion operating power, also known as NCR power, (Nominal Continuous Rating), can be used in operation cost calculations.

**Step 4.** In diesel main engine dimensioning 85-90% of engine loading is used which means the diesel main engine is running at 85-90% of maximum load at full propulsion power, which is the NCR power. The main engine power requirement is

\[
P_{\text{Main Engine TS}} = \frac{P_{\text{Operating power TS}}}{(\text{Main Engine loading } \%)}
\]  

(4)

The required main engine power \( P_{\text{Main Engine TS}} \) is the required MCR (Maximum Continuous Rating) value. After the required main diesel engine MCR power \( P_{\text{Main Engine TS}} \) is determined the selection of two main diesel engines can be made. The closest engine having more power than \( \frac{P_{\text{Main Engine TS}}}{2} \) should be selected from diesel engine manufacturers 2-stroke catalogue. For the Single-Screw system \( P_{\text{Main Engine TS}} \) can be used for main engine selection.

**Auxiliary Engine Dimensioning**

For dimensioning the auxiliary diesel engines the ship’s service, auxiliary, reefer and thruster power need to be known. Service and auxiliary power

\[
P_{\text{Service and auxiliary TS}}
\]  

(5)

for 12000 TEU twin-skeg vessels is approximately 2500 kW. Service and auxiliary power is consumed by normal service load such as lightining, air-conditioning and diesel ancillaries.

 Reefer power can be approximated as

\[
P_{\text{Reefers TS}} = \text{Number of reefers} \times P_{N \text{ Reefer}} \times \text{Load factor}
\]  

(6)

where \( \text{Number of reefers} \) is the total number of reefers on board, \( P_{N \text{ Reefer}} \) the nominal power of one reefer plug, and \( \text{Load factor} \) the average load of all reefers. In large container vessels total reefer load can be at the same level as the service and hotel load of large cruise vessels. The nominal power for 1 FEU (40 foot container) plug is 14 kW. The same plug is also used for 1 TEU container. Electric loads consisting of large numbers of reefers can be modelled with the \( \text{Load factor} \) which gives the average electrical power requirement for a specific number of reefers. This load factor is typically between 50-60%.
Thruster power

\[ P_{\text{Thruster \ TS}} = Number \ of \ thrusters \times P_{\text{N \ Thruster}} \]  \hspace{1cm} (7) 

depends on the total number of thruster motors \textit{Number of thrusters}, and one thruster motor’s nominal power \( P_{\text{N \ Thruster}} \). Two thruster motors are typical for ULCS.

It must be noted that in Twin-Skeg vessels thruster power has to be taken into account when the auxiliary power plant is dimensioned. A ship could at times have a full service load, full reefer load and full thruster load. If ship operator does not want to disconnect part of the reefer load or this is not possible for some reason, power needed for the thrusters should be available from the auxiliary power plant. However, in the CRP concept, when thruster power demand occurs, the ship is in maneuvering mode and Azipod power is low. In this case auxiliary diesel engines reserved for the Azipod can be used to operate the thrusters. Thruster power does not have to be considered when CRP power plant diesel engines for service and auxiliary loads are dimensioned. This benefit means less installed diesel engine power is needed.

Total total power requirement from factors other than propulsion load is the sum of components

\[ P_{\text{Service total needed \ TS}} = P_{\text{Service and auxiliary TS}} + P_{\text{Reefers TS}} + P_{\text{Thruster TS}} \]  \hspace{1cm} (8) 

Transfer losses from the supplying transformers and generators are approximately 4%, figure 5. Taking this into account the the total brake power needed is

\[ P_{\text{Service total needed at brake \ TS}} = \frac{P_{\text{Service total \ TS}}}{(1 - \text{Transfer losses service \ TS \%})} \]  \hspace{1cm} (9) 

\( P_{\text{Service total needed at brake \ TS}} \) is used for auxiliary diesel engine dimensioning. It is the NCR value for the auxiliary engines. In power plant diesel engine dimensioning 90% engine loading is used. The total diesel engine power needed is

\[ P_{\text{Power plant engines \ TS}} = \frac{P_{\text{Service total needed at brake \ TS}}}{(\text{Diesel engine loading \%})} \]  \hspace{1cm} (10) 

\( P_{\text{Power plant engines \ TS}} \) is the MCR value needed for the auxiliary diesel engines. In normal open sea operation the thrusters are not always running. Operation cost is calculated based on operating power

\[ P_{\text{Service operation needed at brake \ TS}} = \frac{(P_{\text{Service and auxiliary TS}} + P_{\text{Reefers TS}})}{(1 - \text{Transfer losses service \ TS \%})} \]  \hspace{1cm} (11) 

After the total required power plant MCR engine power \( P_{\text{Power plant engines \ TS}} \) is determined the diesel engine selection can be made. The adequate diesel engines should be selected from diesel engine manufacturers’ 4-stroke catalogues. One spare generator should be included as a rule of thumb. This offers the possibility of servicing one diesel engine with full power maintained. The total number of power plant diesel engines should be 4-5 units. It is prudent to select same bore size for all auxiliary engines because it will minimize the number of spare parts.
CRP Azipod® System Dimensioning

Main Engine Dimensioning and Diesel Engine Dimensioning for Azipod Power Requirement

The main engine and propulsion power plant dimensioning processes are as follows:

**Step 1.** Define the service speed power requirement

\[
P_{\text{Service speed trial CRP}}
\]  

at sea trial conditions. Service speed power is the shaft power delivered at service speed.

**Step 2.** For container vessels adhering to schedules in any sea condition is very important. To ensure this, a 15-30% sea margin is typically added to the service speed power requirement in trial conditions. The sea margin is added by multiplying service speed power by factor \((1 + \text{Sea margin } \%)\)

\[
P_{\text{Service speed CRP}} = P_{\text{Service speed trial CRP}} \times (1 + \text{Sea margin } \%)
\]  

**Step 3.** In the CRP system propulsion power is delivered by main diesel engine and Azipod. The power split between these two propulsors must be determined. For the hydrodynamic efficiency the optimal power split would be 50%/50%. The power split can be optimized depending on the available main engine and Azipod unit sizes. In the CRP Azipod® system the power ratio between main propeller and Azipod propeller is typically close to 70% and 30%, respectively. This gives shaft power at service speed delivered by the main engine (ME)

\[
P_{\text{Service speed CRP ME}} = P_{\text{Service speed CRP}} \times \text{Power split ME}
\]
and Azipod service speed delivered power

\[ P_{\text{Service speed CRP Azi}} = P_{\text{Service speed CRP}} \times \text{Power split Azi} \]  \hspace{1cm} (15)

\( P_{\text{Service speed CRP Azi}} \) is the power which the Azipod unit delivers to the propeller. It means this power is both the nominal continuous power (NCR) and the maximum continuous power (MCR) of the Azipod unit.

Note! No extra margins are needed for Azipod unit dimensioning because for the electric motor NCR equals MCR i.e. the electric motor can be loaded 100% continuously. For diesel engines, it is typical that NCR = 90% * MCR. In addition, for electric motors there is also the possibility of overloading. Naturally the diesel engines producing power for the Azipod unit have to be dimensioned by the rule NCR = 90% * MCR.

If engine margin is miscalculated for the Azipod unit, this easily leads to overdimensioning of the unit which means extra cost. Main engine output power follows cylinder powers. Currently cylinder power for large 2-stroke engines is 5720 kW. This means main engine power step is 5720 kW. Azipod unit power step size is much smaller. By using the CRP Azipod® system propulsion power need can be matched more precisely because of the smaller power steps, and there is no danger of overdimensioning.

**Step 4.** In order to calculate the required propulsion operating brake power for the main engine, which means the power needed at service speed at the main engine brake, shaftline losses have to be added to shaft power, figure 6. Values between 1.5-3% are typically used.

\[ P_{\text{Operating power CRP ME}} = \frac{P_{\text{Service speed CRP ME}}}{1 - \text{Shaft losses \%}} \]  \hspace{1cm} (16)

For the Azipod power transfer line larger losses have to be used. Losses occur in the propulsion motor, electric drive, drive transformers and generators, figure 6. Propulsion operating power for the Azipod system at the diesel engine brake is

\[ P_{\text{Operating power CRP Azi}} = \frac{P_{\text{Service speed CRP Azi}}}{1 - \text{Transfer losses CRP Azi \%}} \]  \hspace{1cm} (17)

If the following values are used for different network components to obtain Transfer losses CRP Azi = generator efficiency 0.973, transformer and drive efficiency 0.987 and Azipod motor efficiency 0.973, the total efficiency is approximately 0.92 meaning transfer losses of 8 %.

\( P_{\text{Operating power CRP ME}} \) and \( P_{\text{Operating power CRP Azi}} \) are the NCR values for diesel engines. Propulsion operating power can be used for operation cost calculations.

**Step 5.** In main diesel engine dimensioning 85-90% engine loading is used. This means the main diesel engine is at 85-90% of maximum load at full propulsion power. The main engine power requirement is

\[ P_{\text{Main Engine CRP}} = \frac{P_{\text{Operating power CRP ME}}}{\text{Main Engine loading \%}} \]  \hspace{1cm} (18)

The required main engine power \( P_{\text{Main Engine CRP}} \) is the required for the main engine. After the required main diesel engine MCR power \( P_{\text{Main Engine CRP}} \) is determined the
selection of the main diesel engine can be made. The closest engine having more power than $P_{\text{Main Engine CRP}}$ should be selected from diesel engine manufacturers 2-stroke catalogue. From the diesel engine manufacturer’s 2-stroke catalogue the closest engine with higher power than should be selected.

In diesel engine dimensioning for Azipod power 90% engine loading is used. This means diesel engines producing power for the Azipod are at 90% load at full Azipod propulsion power. The required diesel engine power for Azipod is

$$P_{\text{Azipod CRP}} = \frac{P_{\text{Operating power CRP Azi}}}{(\text{Engine loading } \%)}$$  \hspace{1cm} (19)

The total diesel engine MCR power requirement in CRP propulsion concept is

$$P_{\text{Total propulsion need CRP}} = P_{\text{Main Engine CRP}} + P_{\text{Azipod CRP}}$$  \hspace{1cm} (20)

In CRP concept the power plant produces power both for the Azipod unit and the ship’s service and auxiliary (including reefers) systems. To determine the optimal diesel engine and generator sizes, service and auxiliary (including reefers) power requirements have to be established.

**Diesel Engine Dimensioning, Service and Auxiliary Power Requirements**

For dimensioning the diesel engines needed by the non-propulsion load ship’s service and auxiliary, reefer and thruster powers are needed. Service and auxiliary power

$$P_{\text{Service and auxiliary CRP}}$$  \hspace{1cm} (21)

is less for 12000 TEU CRP propulsion vessels than for same size twin-skeg vessels due to larger ancillaries needed for the main engines in the twin-skeg concept. Service and auxiliary power is approximately 1500 kW. Service and auxiliary power is consumed by normal service load such as lighting, air conditioning and diesel ancillaries.

 Reefer power is

$$P_{\text{Reefers CRP}} = \text{Number of reefers} \times P_{\text{N Reefer}} \times \text{Load factor}$$  \hspace{1cm} (22)

where *Number of reefers* is the total number of reefers on board, $P_{\text{N Reefer}}$ the nominal power of one reefer plug, and *Load factor* the average load of all reefers. In large container vessels total reefer load can be at the same level as in large cruise vessels. Nominal power for 1 FEU is 14 kW. Same plug is also used for 1 TEU containers. Electric loads consisting of large numbers of reefers can be modelled with the *load factor* which gives the average electrical power needed for specific number of reefers. This load factor is typically 50-60%. Reefer power is the same for both concepts.

 Thruster power

$$P_{\text{Thruster CRP}} = \text{Number of thrusters} \times P_{\text{N Thruster}}$$  \hspace{1cm} (23)
depends on the total amount of thruster motors \textit{Number of thrusters} and thruster motor nominal power $P_{N\text{ Thruster}}$. Two thruster motors is typical. Thruster power is the same for both concepts.

It must be noted that in twin-skeg vessels thruster power has to be included when the auxiliary power plant is dimensioned. A ship could at times have a full service load, full reefer load and full thruster load. If ship operator does not want to disconnect part of the reefer load or if this is not possible, power needed for the thrusters should be available from the auxiliary power plant. However, in the CRP concept, when thruster power demand occurs, the ship is in maneuvering mode and Azipod power is low. In this case auxiliary diesel engines reserved for the Azipod can be used to operate the thrusters. Thruster power does not have to be considered when CRP power plant diesel engines for service and auxiliary loads are dimensioned. This benefit means less installed diesel engine power is needed.

The total power requirement caused by factors other than propulsion load is the sum of above mentioned load components excluding thruster power

$$P_{\text{Service total needed \ CRP}} = P_{\text{Service and auxiliary \ CRP}} + P_{\text{Reefers \ CRP}} \tag{24}$$

Transfer losses from the supplying transformers and generators are the same as in the twin-screw system, approximately 4\%, figure 6. Taking these losses into account the the total brake power needed is

$$P_{\text{Service total needed at brake \ CRP}} = P_{\text{Service total needed \ CRP}} / (1 - \text{Transfer losses}_{\text{CRP Service \ %}}) \tag{25}$$

$P_{\text{Service total needed at brake \ CRP}}$ is used for dimensioning the diesel engines. It is the NCR value for the engines. In normal open sea operation the thrusters are not always running. Operation cost is calculated based on operating power

$$P_{\text{Service operation needed at brake \ CRP}} = P_{\text{Service total needed at brake \ CRP}} \tag{26}$$

In auxiliary diesel engine dimensioning 90\% engine loading is used. Again, full service and auxiliary (including reefers) power is the total power without thrusters. The required diesel engine MCR power is

$$P_{\text{Power plant engines service \ CRP}} = P_{\text{Service total needed at brake \ CRP}} / (\text{Diesel engine loading \ %}) \tag{27}$$

Total required MCR power including Azipod, service and auxiliary power is

$$P_{\text{Power plant engines \ CRP}} = P_{\text{Power plant engines service \ CRP}} + P_{\text{Azipod \ CRP}}$$

The selection for diesel engines in the CRP system can now be made. The adequate diesel engines should be selected from diesel engine manufacturers’ 4-stroke catalogues. One spare generator should be included as a rule of thumb. This offers the possibility of servicing one diesel engine with full power maintained. The total number of power plant diesel engines should be 4-5 units. In the CRP system also, it is prudent to select same bore size for all auxiliary engines because it will minimize the number of spare parts.
To conclude the discussion of the dimensioning processes for twin-screw and CRP systems, the following can be stated:

1. To obtain verified information on the propulsion powers required for different propulsion systems model tests have to be carried out. Model tests performed so far have verified an 11.4% hydrodynamic benefit for the CRP propulsion system when compared with the twin-screw twin-skeg system.

2. In the CRP system the power split between main engine and Azipod unit is not fixed. It can be varied within certain limits, depending on the power steps of the main engine in order to minimize the first cost of propulsion machinery.

3. Unlike diesel engines, no engine margin is needed for the Azipod unit. Due to the electric motor inside the Azipod, NCR equals MCR for the Azipod unit. However, diesel engines in the power plant supplying power for the Azipod unit need to be dimensioned normally by the rule NCR = 90% * MCR.

4. In the CRP system bow thruster power can be neglected in auxiliary power plant dimensioning. In maneuvering mode when bow thrusters are operated, Azipod power is low creating more than enough capacity to supply the bow thrusters. This means less installed power in the power plant.

**Electric network**

Service, auxiliary and reefer load in ULCSs can easily exceed 10 MW - the same consumption as today’s large cruise vessels. Consequently, the electrical network has to be made by using medium voltage systems. These have been well proven in numerous cruise vessels where delivered service power runs up to 10 MW and electrical propulsion power up to 42 MW. When utilizing the CRP Azipod system in ULCSs, there is no difference when compared with the twin-screw system, which should also use a medium voltage system.
CRP Azipod vs Twin-Skeg System: Operation Cost Comparison

Due to the CRP Azipod® system’s benefits in hydrodynamic efficiency considerable savings in operation costs can be achieved. The basis for the following operation cost comparison is the 12000 TEU vessel size. Three different propulsion systems have been considered: CRP, twin-screw twin-skeg and single-screw systems, table 1. The single screw system is not viable for this vessel size due to propeller manufacturing and operational problems but it has been considered as a hypothetical option.

Table 1. Main dimensions of the 12000 TEU vessel.

<table>
<thead>
<tr>
<th>Main Dimension</th>
<th>CRP [m]</th>
<th>Twin ME [m]</th>
<th>Single ME [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>Breadth</td>
<td>54.4</td>
<td>54.4</td>
<td>54.4</td>
</tr>
<tr>
<td>Depth</td>
<td>27.3</td>
<td>27.3</td>
<td>27.3</td>
</tr>
<tr>
<td>Draught</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
</tr>
<tr>
<td>DWT MT</td>
<td>157 000</td>
<td>157 000</td>
<td>157 000</td>
</tr>
<tr>
<td>Gross Tonnage</td>
<td>158 500</td>
<td>159 100</td>
<td>158 500</td>
</tr>
</tbody>
</table>

In operation cost calculation fuel and lubrication oil consumption as well as maintenance costs both for the main engines and auxiliary engines have been taken into account. Fuel and lubrication oil consumption are based on 6000 h annual operation at full speed. Propulsion power used in the calculations includes sea margin. In normal seafaring four auxiliary engines are needed.

Operation at lower speeds has not been included in the calculation. Due to the power plant principle the CRP system utilizes these operation modes will be even more advantageous for the CRP concept than full-speed operation because the power plant engines can be loaded close to optimal loading. This means further savings in fuel consumption, which could have significant impact on total operation costs because on some routes full speed may be applied for only 50% of the total voyage time.

Fuel and lubrication oil consumption and maintenance costs are based on selected diesel engines and their loading rates. Consumption and maintenance costs have been received from engine manufacturers. The machinery has been selected based on the total power need on board. Machinery data, engine loadings, loads and data used in operation cost calculation are presented in table 2.
Table 2. Operation cost calculation data for 12000 TEU vessel.

<table>
<thead>
<tr>
<th>Main Engine Data</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine(s)</td>
<td>1 x Sulzer 10RTA96C</td>
<td>2 x Sulzer 8RTA96C</td>
<td>1 x 15K98MC</td>
</tr>
<tr>
<td>Main engine MCR [kW]</td>
<td>97 200</td>
<td>91 520</td>
<td>85 800</td>
</tr>
<tr>
<td>Main engine [%]</td>
<td>30 %</td>
<td>30 %</td>
<td>30 %</td>
</tr>
<tr>
<td>Main engine loading [%]</td>
<td>90 %</td>
<td>87 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Azipod unit power [kW]</td>
<td>20 550</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total installed propulsion power [kW]</td>
<td>82 018</td>
<td>91 520</td>
<td>85 800</td>
</tr>
<tr>
<td>Auxiliary Engine Data</td>
<td>CRP</td>
<td>Twin ME</td>
<td>Single ME</td>
</tr>
<tr>
<td>Auxiliary engines</td>
<td>5 * 8L32 / 2 * BL56A</td>
<td>5 * BL32</td>
<td>5 * BL32</td>
</tr>
<tr>
<td>Total installed Aux engine power [kW]</td>
<td>43 440</td>
<td>18 000</td>
<td>18 000</td>
</tr>
<tr>
<td>N.o. of aux engines in normal operation</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Auxiliary engine loading [%]</td>
<td>85 %</td>
<td>76 %</td>
<td>72 %</td>
</tr>
<tr>
<td>Total installed power [kW]</td>
<td>109 520</td>
<td>109 520</td>
<td>103 800</td>
</tr>
<tr>
<td>Auxiliary and Service Load</td>
<td>CRP</td>
<td>Twin ME</td>
<td>Single ME</td>
</tr>
<tr>
<td>Service load [kW]</td>
<td>1 500</td>
<td>2 500</td>
<td>2 000</td>
</tr>
<tr>
<td>Bow thruster load [kW]</td>
<td>0</td>
<td>4 400</td>
<td>4 400</td>
</tr>
<tr>
<td>Reefer load [kW]</td>
<td>8 000</td>
<td>8 000</td>
<td>8 000</td>
</tr>
<tr>
<td>Total needed aux and service power [kW]</td>
<td>10 995</td>
<td>17 245</td>
<td>16 667</td>
</tr>
<tr>
<td>Losses</td>
<td>CRP</td>
<td>Twin ME</td>
<td>Single ME</td>
</tr>
<tr>
<td>Shaftline losses [%]</td>
<td>2 %</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Electric losses for propulsion [%]</td>
<td>8 %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electric losses for service and auxillary [%]</td>
<td>4 %</td>
<td>4 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Operation Cost calculation data</td>
<td>CRP</td>
<td>Twin ME</td>
<td>Single ME</td>
</tr>
<tr>
<td>Annual operating hours [h]</td>
<td>6 000</td>
<td>6 000</td>
<td>6 000</td>
</tr>
<tr>
<td>Operating brake power, Main engine</td>
<td>51 338</td>
<td>79 714</td>
<td>77 382</td>
</tr>
<tr>
<td>Operating brake power, Aux engines for pod</td>
<td>22 336</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operating brake power, Aux engines for service</td>
<td>9 896</td>
<td>10 938</td>
<td>10 417</td>
</tr>
<tr>
<td>Main engine SFOC [g/kWh]</td>
<td>166.8</td>
<td>166.8</td>
<td>166.8</td>
</tr>
<tr>
<td>Aux engine SFOC [g/kWh]</td>
<td>172</td>
<td>183</td>
<td>183</td>
</tr>
<tr>
<td>HFO price [USD/t]</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>LCV (Lower Calorific Value) [kJ/kg]</td>
<td>42 700</td>
<td>42 700</td>
<td>42 700</td>
</tr>
<tr>
<td>LO price main engine [USD/t]</td>
<td>1 000</td>
<td>1 000</td>
<td>1 000</td>
</tr>
<tr>
<td>LO price pod and auxiliary engine [USD/t]</td>
<td>1 000</td>
<td>1 000</td>
<td>1 000</td>
</tr>
<tr>
<td>SFOC LO ME [g/kWh]</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>SFOC LO Aux engine [g/kWh]</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Specific maintenance cost ME [USD/MWh]</td>
<td>0.86</td>
<td>0.89</td>
<td>0.59</td>
</tr>
<tr>
<td>Specific maintenance cost Aux engine [USD/MWh]</td>
<td>2.00</td>
<td>2.40</td>
<td>2.40</td>
</tr>
</tbody>
</table>

First cost of the selected 2- and 4-stroke diesel engines is presented in table 3. First cost is calculated using a unit price of USD 210/kW.

Table 3. First cost of diesel engines in 12000 TEU vessel.

<table>
<thead>
<tr>
<th>Diesel Engine First Cost</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed diesel engine power [ME + Aux] [kW]</td>
<td>100 640</td>
<td>109 520</td>
<td>103 800</td>
</tr>
<tr>
<td>Total main engine price [USD]</td>
<td>12 012 000</td>
<td>19 219 200</td>
<td>18 018 000</td>
</tr>
<tr>
<td>Total Aux engine price [USD]</td>
<td>9 122 400</td>
<td>3 780 000</td>
<td>3 780 000</td>
</tr>
<tr>
<td>Total diesel engine price [USD]</td>
<td>21 134 400</td>
<td>22 999 200</td>
<td>21 798 000</td>
</tr>
<tr>
<td>Difference in USD</td>
<td>0</td>
<td>1 864 800</td>
<td>663 600</td>
</tr>
</tbody>
</table>

From a ship building point of view, remarkable savings can be seen when a vessel utilizing the CRP system is compared with a twin-skeg vessel. This is due to reductions in engineering and construction hours as well as the amount of steel. Savings in engineering and construction work can be realized in foundations of the slow speed engines, shaftlines, exhaust system, steering gears, rudders and painting of the hull. When savings in all of these sub items are combined, the total cost of shipbuilding, when utilizing the CRP system, including machinery, is very attractive.
Annual fuel and lubrication oil consumption as well as maintenance costs are presented in detail in table 4. It can be clearly seen that fuel consumption is economically the most important element of operation cost. When comparing CRP with twin-skeg and CRP with single-screw, savings in fuel are 8% (MUSD 1.07) and 4% (MUSD 0.56), in lubrication oil 24% (MUSD 0.11) and 21% (MUSD 0.09) and in maintenance –24 % (MUSD 0.96) and –25 % (MUSD 0.17) per annum, respectively.

Total annual operation cost savings gained using the CRP system compared to the twin-screw system is 8% (MUSD 1.07), and 4% (MUSD 0.56) compared to the hypothetical single-screw system.

Table 4. Annual operation cost calculation results for 12000 TEU vessel, fuel and lubrication oil consumption, costs and relative differences between propulsion systems.

<table>
<thead>
<tr>
<th>Fuel Costs</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine, annual fuel consumption [t]</td>
<td>7977</td>
<td>7777</td>
<td>7744</td>
</tr>
<tr>
<td>Annual fuel consumption pod [t]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Annual fuel consumption auxiliary [t]</td>
<td>12009</td>
<td>11438</td>
<td>11438</td>
</tr>
<tr>
<td>Total annual fuel consumption [t]</td>
<td>91787</td>
<td>86881</td>
<td>86881</td>
</tr>
<tr>
<td>Total annual fuel cost [USD]</td>
<td>13768054</td>
<td>13332186</td>
<td>13332186</td>
</tr>
<tr>
<td>Relative difference</td>
<td>108%</td>
<td>105%</td>
<td>105%</td>
</tr>
<tr>
<td>Difference in USD</td>
<td>1071693</td>
<td>635826</td>
<td>635826</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lub Oil Costs</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine, annual LO consumption [t]</td>
<td>526</td>
<td>526</td>
<td>511</td>
</tr>
<tr>
<td>Aux engines, annual LO consumption pod [t]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aux engines, annual LO consumption auxiliary [t]</td>
<td>39</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Total annual LO consumption [t]</td>
<td>565</td>
<td>565</td>
<td>546</td>
</tr>
<tr>
<td>Total annual LO cost [USD]</td>
<td>565487</td>
<td>549220</td>
<td>549220</td>
</tr>
<tr>
<td>Relative difference</td>
<td>124%</td>
<td>121%</td>
<td>121%</td>
</tr>
<tr>
<td>Difference in USD</td>
<td>1622</td>
<td>93356</td>
<td>93356</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maintenance Costs</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine, annual maintenance cost [USD]</td>
<td>226512</td>
<td>378893</td>
<td>303732</td>
</tr>
<tr>
<td>Auxiliary engines, annual maintenance cost [USD]</td>
<td>456120</td>
<td>297360</td>
<td>297360</td>
</tr>
<tr>
<td>Total annual maintenance costs [USD]</td>
<td>682632</td>
<td>586253</td>
<td>511092</td>
</tr>
<tr>
<td>Relative difference</td>
<td>100%</td>
<td>86%</td>
<td>75%</td>
</tr>
<tr>
<td>Difference in USD</td>
<td>96379</td>
<td>171540</td>
<td>171540</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Operation Costs</th>
<th>CRP</th>
<th>Twin ME</th>
<th>Single ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fuel, LO and maintenance cost [USD]</td>
<td>13833857</td>
<td>14919793</td>
<td>14391498</td>
</tr>
<tr>
<td>Relative difference</td>
<td>100%</td>
<td>108%</td>
<td>104%</td>
</tr>
<tr>
<td>Difference in USD</td>
<td>0</td>
<td>1085936</td>
<td>557641</td>
</tr>
</tbody>
</table>

Total annual fuel, lubrication oil and maintenance costs are present in figure 7.

Figure 7. Operation cost calculation results for 12000 TEU vessel: total annual cost of fuel, lubrication oil and diesel engine maintenance.
In figure 8, annual operational savings (MUSD 1.07) compared to the twin-screw system are discounted using a 10% interest rate to obtain the NPV of the savings. Accumulated income over a 15-year period is approximately MUSD 8.26. Revenue from increased container capacity can also be taken into account. With the following conservative assumptions:

- USD 200 net income per container
- 100 extra containers per voyage
- 12 voyages per year

Total accumulated savings over a 15-years period increase by 1.8 MUSD to more than MUSD 10.

Figure 8. Cumulative operational savings offered by CRP system in 12000 TEU vessel, including fuel, lubrication oil, maintenance and 100 extra containers. Interest rate 10%, USD 200 net income per container, 100 extra containers, 12 voyages per year.

Other value creators like faster maneuvering and faster port entrance which would generate extra income due to the extra time saved for the voyage (lower voyage speed) are not evaluated in this operation cost comparison.

**Conclusion**

Calculations clearly show that the CRP Azipod® propulsion system is the best choice for ULCSs of 12000 TEU size and beyond. Model tests demonstrate an 11.4% benefit in propulsion power requirement which means less installed diesel engine power is needed on board. With The CRP system, propulsion power can be produced with optimum machinery, thus minimizing operation costs.

In power plant dimensioning the CRP concept offers benefits resulting from the flexible power plant principle applicable in bow thruster operation. Furthermore, the CRP system provides remarkable savings in operation costs due to lower fuel
consumption. When hydrodynamic efficiency, less installed diesel engine power, power plant principle and extra cargo-carrying capability are combined, savings can top MUSD 10 over a 15-year period when compared with the twin-screw twin-skeg system.

The CRP Azipod® propulsion concept offers clear economic benefits not only for ULCSSs but for other ship types as well. ROPAX, LNG carriers and tankers can also take full advantage of these benefits.

References

