Mapping the Hybrid Solution Space

John Buckingham  
Chief Mechanical Engineer  
BMT Defence Services Ltd, UK  
Email: JohnB@bmdsl.co.uk

ABSTRACT

The use of an electric machine in parallel with a ship’s main engine offers a hybrid design that can offers modest fuel savings and also reduce engine running hours. When operating as an electric motor, the machine allows the Diesel Generators (DG Sets) to provide the combined power demand to the Ships Electrical Load (SEL) and the propellers whilst the machine operates as an alternator when running on the main engines at higher speeds.

BMT have recent experience of how such a design is achieved and in this paper a representative small tanker is used as an example to demonstrate the benefits of a hybrid design and some of the issues involved in its design definition, especially the combinator curve. As modern commercial vessels are increasingly operating at a range of speeds, the assessment of the effects of a wide operating profile has some relevance.

The hybrid design requires an engine combinator curve to allow the main engine to supply power to the SEL whilst meeting the propeller requirement for any given speed. As the changes to the efficiency of the main power and propulsion units (machine, gearbox, main engine and propeller) vary only slightly with changes in load this paper explores the issues that surround the definition of the combinator curve to achieve the best overall performance in terms of fuel economy.

Keywords: Energy efficiency, hybrid propulsion

Context

The introduction of hybrid drives means the designer has to consider the twin loads on the main engine: the propeller load and the electrical generator load. As the latter load can be up to one quarter of the former, this puts into the question the issue of the characteristic of the combinator curve, the curve which states the relationship between the power and speed of the main engine. Normally the combinator curve is set to allow the engine to operate at a balanced state where it is near its most efficient speed for a given load (i.e. the lowest specific fuel consumption (Sfc)) whilst also offering a lower speed for the same power demand to allow for a better propeller efficiency.

When an electrical Power Take-Off (PTO) generator load is applied, this may affect the decisions to be made when defining the combinator curve.

This study seeks to understand the impact of a number of combinator curves on a basic mechanical propulsion design and then consider how the same changes affect a hybrid design. The study seeks to identify the differences in overall fuel efficiency between the set of combinator curves and how they affect the two different Power and Propulsion (P&P) system arrangements.

Ship Particulars

An 11,000 tonne dwt chemical tanker has been used as an example platform for this set of studies. The ships principal characteristics are provided in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadweight in tonnes</td>
<td>11,293</td>
</tr>
<tr>
<td>Displacement tonnes</td>
<td>14,117</td>
</tr>
<tr>
<td>Length in m</td>
<td>117.0m</td>
</tr>
<tr>
<td>Beam in m</td>
<td>19.0m</td>
</tr>
<tr>
<td>Draught in m</td>
<td>7.4m</td>
</tr>
</tbody>
</table>
The ship’s operating profile is defined so that the relative time spent at each speed is reflected in the balance of fuel consumption and the overall choice of combinator curve. The assumed operating profile for sea state 4 is shown in Figure 1. Sea state 4 is chosen as this is the most prevalent sea state condition in the world’s oceans. The speed-time breakdown reflects the time spent at sea in a range of speeds to allow for voyage routing, just-in-time arrivals. 80% of the time is spent the top two speeds with the balance being allocated to much slower speeds for when approaching the destination port and for transiting through confined waterways.

The time-speed profile demonstrates how ships of the same design can be operated in different ways and how the P&P system needs to be flexible to allow for changes to ship operations through its life. In higher sea states the profile will be altered with no time spent at the higher speeds and more time spent at lower speeds. Thus when considering a P&P system as a whole, the complete set of sea states needs to be considered to ensure that the operating envelopes of the machinery are fully defined. However in this paper the assessment is limited to SS4 for brevity.
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**Diesel Mechanical**

The Diesel Mechanical (DM) design has a single controllable pitch propeller (CPP) driven by a 4,000kW medium-speed main engine through a reduction gearbox.

![Figure 2: DM Design: Engine Loadings](image)

Figure 2 shows how the main engine’s load increases steadily. Note how the engine load rises towards zero knots due to poor propeller efficiency. Figure 3 shows the engine’s power-speed envelope and a basic combinator curve which is not optimised for the engine power-speed characteristic. The ship’s speeds are also shown on the plot. Note the cluster of points at slow speeds where the improving propeller efficiency and the increasing resistance almost cancel each other out.

![Figure 3: Basic Combinator Curve](image)
**Hybrid Design**

The hybrid P&P system is a COmbined Diesel eLectrical Or Diesel (CODLOD) arrangement. This is a variant of the single shaft DM arrangement, where the shaft is driven either by a 4,000kWb main engine OR a Hybrid Machine (HM), coupled to a reduction gearbox to drive a CPP.

The HM are asynchronous (induction) machines and can act as either a propulsion motor to drive the shaft or as a variable-speed shaft generator providing power to the Ship’s Electrical System (SES). When operating in motor mode, each HM provides up to 300kW of propulsion power to the shaft. The HM is driven through the power converters which are supplied from the generating side of the SES which is supplied from the DG sets. The motor would drive into the gearbox through the Power Take-Off (PTO) shaft and allow the main engines to be shut-down and de-clutched.

All variable-speed AC propulsion motors have a Variable Speed Drive (VSD) power converter to provide speed and torque control. The VSD employs a four-quadrant power converter in the form of an Active Front End (AFE) which allows power flow during manoeuvring. However during a crash-stop the AFE may not be used to allow power to be absorbed back through the HM to the SES because the design makes use of the CPP to facilitate thrust reversal for braking. This avoids the need for Dynamic Braking Resistors and other means of handling regenerative power. But nevertheless the AFE has a critical use: operating in generator mode the HM generators are driven by the main engine through the gearbox and the AFE then allows up to 500kWe of power to be generated.

Two 372kWe DG sets provide electrical power to the SES and these can operate in parallel with the HM when it is operating in generator mode.

The hybrid design makes a virtue of the likely available propulsion capacity of the ship which can be used to also generate electrical power. This increase in load also increases the main engines overall efficiency and may mean that fewer, if any, DG sets need to be run.

In a hybrid arrangement the main engine drives the propeller shaftline and also drives the motors which are acting as alternators. Most medium-speed main engines allow for a generous torque-speed characteristic in the mid-speed range: this allows the main engines to provide the propulsion power on the cubic-law propeller curve and also to supply the SEL at an offset to the propeller curve.

Ships power from the main engines means such power is being generated from a bigger engine with typically a better Sfc than the smaller DG sets. For most of the range of interest, we have found that if the ratio of engine cylinder sizes (main engine to DG set engine) is greater than 1.5 then the 6% losses due to the AFE and the gearbox transmission are on parity with the use of the DG set with the motor and DG alternator losses assumed to be equal. This ratio is however very dependent on engine selection and hence a hybrid solution needs to be tailored to each ship and its usage for it to realise energy savings.
Figure 4: Hybrid Schematic

Figure 4 shows a simplified schematic of the relationship between the main engine and the DG sets.

Figure 5: Mechanical & Hybrid Designs: Engine Loadings

Figure 5 shows the motors in the Hybrid drive design only driving the ship to 2 knots before the propulsion is provided by the main engine. For speeds above 2 knots the main engine supplies power to the propeller and the SEL. At speeds above 7 knots the main engine provides power to meet the SEL and the DG sets are turned off.
Figure 6 shows how the motor only operates at slow speeds for manoeuvring and slow passage in confined waters. From 7 knots onwards the main engine is able to provide power to the SEL: this avoids having to run the DG sets.

Figure 7 shows how the hybrid design has a 2.5% lower fuel consumption at top speed.
Combinator Curves

Figure 8 shows the power-speed characteristic of the main engine with the lines depicted in the legend showing the range of combinator curve. The set of combinator curve comprises:
1. cc-0: Standard general combinator curve - non-optimised for this engine;
2. cc-1: A general combinator curve for this engine;
3. cc-2: A combinator curve which passes through the points of best Sfc for each power;
4. cc-3: A combinator curve which seeks to operate at the slowest possible speed for each power.

Figure 8: Main Engine Combinator Curves

Figure 8 shows how combinator curve 1 tracks the power line but at a safe margin to allow for engine surge. Combinator curve 3 follows a closer more risky line which would require higher gain propeller controls to ensure the stall line is not exceeded for longer than is permitted by the engine supplier.

Combinator curve 2 follows the set of points which represents the lowest Sfc for a given power. This line tends to lead to higher engine speeds for a given power demand.

DM Comparisons

Fuel Consumption
The machinery definition and loading together with the fuel consumption at each integer speed has been identified using the BMT proprietary tool, Ptool (Ref 1). The tool allows the P&P System behaviour to be defined for all points between the fuel and the sea water. The four DM designs each with a different combinator curve were run on Ptool and then compared to allow the different performance to be identified.
Figure 9 shows how fine the fuel consumptions differences are between the different DM designs. At different speeds, different combinator curves provide the best benefit with combinator curve 3 being the most beneficial at higher speeds where the ship speeds much of its time and the propulsion power and the fuel consumption is higher.

The change of combinator curve affects the operating point of the engine which also changes the speed and the operating point of the propeller. If the combinator curve is further to the left for a given engine power load, the engine shaft speed is slower and thus so is the propeller shaft. For a given thrust the blade pitch is slightly higher and these conditions lead to a better propeller efficiency, which in turn demands less power from the engine.

Figure 10 shows how the combinator curves affect the propeller speeds with combinator curve #3 leading to the slowest overall shaft speed profile.
However this may lead to the engine being away from its best efficiency point for the given speed. These studies seek to identify which combinator curve is most suitable for the best overall P&P system performance.

Figure 11: DM Designs: Propeller efficiencies

Figure 11 shows the effect of the propeller speeds on their efficiencies: in general, the slower propeller for a given thrust has the best efficiency.

Figure 12: DM Design: Sfc

Figure 12 shows the variation of the overall Sfc across the speed range. Note how combinator curve 2 which follows the path of best (i.e. lowest) Sfc has the lowest Sfc overall.
Figure 13: DM Design: Baseline Overall Fuel Consumption

Figure 13 shows the comparison of the overall fuel consumption with the four combinator curves using the DM design on combinator curve 1 as the baseline. The DM design with the best fuel consumption benefit (4.48% fuel saving) is combinator curve 3 where the engine speed for a given power is as low as possible.

Crash Stop

A crash stop capability is required to ensure the ship can stop safely to avoid hazards. In a four-stroke engine propulsion system a common machinery sequence is for the main engine speed to be reduced to near idle before the CPP blade angles are reversed and the engine speed increased. At slow speeds the engine speed and blade angle are controlled to ensure the thrust block loading is not exceeded.

Figure 14: Crash stop machinery sequence

Figure 14 shows a possible sequence of machinery changes for a crash stop manoeuvre of the tanker. When the crash stop performance of the four DM designs was compared, the design with the low-speed combinator curve (cc-3) stopped 4% shorter than the baseline (cc-0).
Hybrid Designs

Figure 15 shows the torque-speed characteristic of the hybrid machine with the efficiency contours shown in blue.

![Figure 15: Hybrid machine torque-speed](image)

Overlaid on Figure 15 are the motor curves (to the left) and the generator curves (to the right). When operating as a motor the propeller pitch is set to full and so all designs have the same characteristic.

All generator loads were the same amongst the different hybrid designs so that they all follow a constant power curve. Due to the changes in propeller speed due to the different combinator curves the generator speeds for each design are all different. The best-Sfc combinator curve led to a faster speed and this is shown in magenta to the right. In general it would appear that for a machine efficiency carpet plot such as the one shown, when the machine is operating as a generator it is slightly more efficient when operating at slower speeds.

![Figure 16: Hybrid Combinator Curve Benefits](image)
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Figure 16 shows how combinator curve #3 provides the lowest fuel consumption of the hybrid designs.

![Figure 16](image)

**Figure 16: Combinator Curve Comparison**

Figure 17 shows how combinator curve #3 provides the lowest fuel consumption of the hybrid designs.

![Figure 17](image)

**Figure 17: DM v Hybrid: Fuel Consumption**

Figure 17 shows how combinator curve #3 provides the lowest fuel consumption of the hybrid designs. The hybrid offers the greatest benefit at full speed but below this the DM design is more fuel efficient. For sea states below SS4 this will allow the hybrid to yield greater fuel efficiency.

**Conclusions**

A four-stroke propulsion system design requires combinator curves to allow the engine to be matched to the propeller. In this study some variants to the usual curves have been explored and it is found that where possible, a slower speed for a given engine power demand is preferable for reduced fuel consumption. This has a greater impact than a curve where the engine speed is set to give the best Sfc for a given power demand.

Hybrid designs are a relatively new phenomenon, being advanced through the benefits of cheaper and robust power electronics modules. Used judiciously they offer fuel savings through the use of the main engine’s better inherent fuel efficiency compared to DG sets. The use of a slower speed combinator curve also provides a slightly beneficial efficiency to the machine when it is operating as a generator as the slower machine speed may bring it closer to the point of best machine efficiency. However the machine design therefore needs to be mindful of the required P&P system performance.

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**REFERENCES**