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Early Efficiency Estimation of Hybrid and Electric Propulsion Systems on Board Ships

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***Abstract*—This paper presents a methodology for evaluating different on-board power systems in the concept design phase. From an energy efficiency perspective, the potential advantages of a modern on-board power system are dependent on two major considerations: the design ratio between propulsion and auxiliary loads and the operational profile. These factors vary significantly for different ships and they can be roughly estimated very early in the design process, when only the main ship functions are known. An energy efficiency calculation method is proposed that has only these factors as input and is therefore applicable in the early stages of ship design.**

I. INTRODUCTION

Environmental concerns and the diminishing supply of fossil fuels have led to significant time and resources being devoted to research and development in the energy field. Not a small part of this research is dedicated to improving energy efficiency of power systems. Different applications will naturally pose specific challenges. In the maritime sector, one of the hardest challenges to overcome is the enduring competitiveness of classical mechanical propulsion, even in terms of fuel efficiency.

There are two main advantages of mechanical propulsion: the fact that the engine can be run at variable speed (which leads to better fuel consumption at low loads) and the low associated transmission losses. While opting for an all-electric ship or a ship with hybrid transmission can still lead to improved energy efficiency, this is only true for specific applications. Nevertheless, the applicability of electric and hybrid transmission is expanding [1]–[3].

Chalfant [4] identifies three distinct stages of ship design: concept design, engineering design and production design. Research into improving the concept design stage (when the general configuration of the power system is chosen) is either focused on specific cases [5]–[8] or on advanced optimization algorithms or software [9]–[12]. Similarly, a significant amount of research has been dedicated to the engineering design stage of all-electric ships and hybrid transmission. Such studies are generally about the optimal design or control of a given configuration [13]–[21]. Naturally, production design takes place outside the research community.

The selection of mechanical, electrical and hybrid propulsion takes place during the concept design stage. However, to the best of our knowledge, no software or algorithm is currently in place to guide the decision maker in such a choice if limited ship data is available. To that effect, the objective of the present work is a quick alternative method of estimating energy efficiency which is suitable for the early phases of conceptual design.

The next section will give an overview of the method proposed to achieve this objective, describing the propulsion systems considered, the input variables necessary and the proposed algebraic model used. The following section shows the relative performance of modern systems when compared to classical mechanical propulsion depending on various aspects of the ships' functions. The results will be discussed more thoroughly in a separate section. Lastly, the paper ends with the conclusions which can be drawn from the present work.

II. METHOD OVERVIEW

A. Propulsion Systems

Four types of propulsion systems are considered:

1) The benchmark case represents the classic mechanical propulsion with separate generator sets for the auxiliary loads.
2) Electric AC propulsion consists of a fully integrated grid. Power for both propulsion and auxiliary loads is supplied by generator sets. The generators sets are run at constant speed to ensure a stable AC frequency.
3) Electric DC propulsion is similar to the item above with the notable difference that a rectifier is used after the generator sets to convert the current from AC to DC. As frequency is no longer an issue, variable speed of the engine is possible
4) Hybrid propulsion is comprised of a main propulsion engine connected to the auxiliary system (supplied by generator sets) by a shaft motor/generator. The shaft motor/generator allows for power to either be taken out of the shaft and into the auxiliary systems(Power Take-Out/PTO) or from the auxiliary generator sets and into the shaft (Power Take In /PTI).

B. Input Variables

The proposed design exploration method takes place in two steps. The first step is performed very early in the design stage, when only the approximate split between propulsion and auxiliary loads is known. The variable chosen to reflect this is the design percentage of the propulsion load. In other

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words, the percentage of the installed power provided by the propulsion engine in the benchmark case. In the present case, auxiliary loads are assumed to be electrical. Depending on the type of ship in question they can be comprised of HVAC systems, hotel loads, dredging pumps, weaponry or any other equipment running on electricity. For this step, the results presented are averaged over the entire operating range of the system, assuming an uniform operational profile.

For the second step, the design percentage of the propulsion load is assumed and the influence of the operational profile is explored. While the common way of expressing a ships' operational profile (through a histogram detailing the load distribution) already provides some valuable insight, the split between propulsion and auxiliary loads is also very important in determining the relative efficiency of alternative power systems. Note that here the instantaneous split between the two types of load is considered. To that effect, we propose an array format for the operational profile, in which the row indices represent the propulsion load, the column indices the auxiliary load and the values in the array the percentage of time spent at the loading scenario defined by the two indices. To support the evaluation of efficiency based on an operational profile given in this format, the relative efficiency will be calculated for modern systems for different instantaneous splits.

C. Modelling Approach

The relative efficiencies presented in the results are based on algebraic models and account only for the different specific fuel consumption curve of the engines at constant and variable speed and the different transmission losses between the considered power system configurations(Equation (1)). The speed-torque profile required by propellers is very close to the engine optimum in therms of part-load efficiency. The propeller curve was therefore used for the variable speed situation. For each of the four configurations Equation (1) was used to calculate the specific fuel consumption for all possible combinations of auxiliary loads (al) and propulsion loads(pl). The obtained values were averaged over all loading cases (asuming an average distribution) to investigate design choices independent of operational profile. Since mechanical propulsion is still the industry standard it was used as a becnhmark and all presented efficiencies are relative to it.

$$sfc(pl, al) = \frac{dps \times pl \times sfc(pl)}{\eta_{transmission_{pl}}} + \frac{das \times al \times sfc(al)}{\eta_{transmission_{al}}} \quad (1)$$

Where:

sfc=specific fuel consumption as function of load [g/kWh];

pl=propulsion load [$\%dps$];

al=auxiliary load [$\%das$];

dps=design propulsion split [%];

das=$1 - dps$=design auxiliary split[%];

$\eta_{transmission_{pl}}$=combined efficiency of transmission elements from engine to propeller shaft [-];

$\eta_{transmission_{al}}$=combined efficiency of transmission elements from engine to grid [-];

TABLE I
OVERVIEW OF THE CONFIGURATIONS CONSIDERED

Configuration	Loading Case	Engine curve	Transmission Elements
Benchmark	Propulsion Auxiliary	propeller constant speed	gear box generator
Electric AC	Propulsion Auxiliary	constant speed constant speed	generator, controller, motor generator
Electric DC	Propulsion Auxiliary	propeller propeller	controller, motor generator
Hybrid	Propulsion Auxiliary PTO PTI	propeller constant speed propeller constant speed	gear box generator generator, controller controller,motor

Table I shows which specific fuel consumption curves and relevant transmission losses are used for each configuration. An additional term is added to the formula in the case of hybrid propulsion if PTO/PTI is in effect. Moreover, as this configuration (hybrid) allows for multiple ways of dividing the load between the two power sources (propulsion engine and generator sets), the specific fuel consumption was calculated for all viable load divisions and the minimum value was considered. Downsizing is reflected in Equation (1) by adjusting the loading condition for which the specific fuel consumption is calculated.

III. RESULTS

A. Design Load Requirements

Figure 1 shows that the ratio between propulsion and auxiliary power have a considerable impact on the relative efficiency of alternative propulsion systems, even when an average is taken over the entire operating range. While the variation of relative efficiency is more pronounced for different loading scenarios, as will be shown in Section III-C, the figure indicates that ships with higher relative auxiliary loads are more likely to benefit from electric or hybrid propulsion. Moreover, the percentage of operating scenarios where fuel savings are possible will also be higher (Figure 2).

B. Downsizing

An advantage of having a completely connected system (electric or hybrid) is the possibility of reducing the maximum installed load. Figure 3 shows an example of the average relative efficiency achievable for different reductions in the total installed load(downsizing).Assuming that the same safety factors need to be maintained, the theoretical maximum downsizing possible is given by the minimum between the installed propulsion power and installed auxiliary power, in the corresponding mechanical propulsion system. A more precise estimation can be made from the operational profile given in the suggested array format.

C. Operational Profile

The operational profile of the ship is a well known factor in the design of modern power systems. However, as

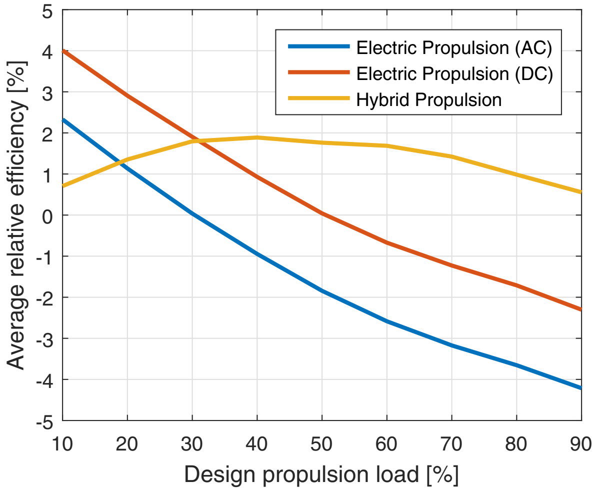

Fig. 1. Average relative efficiency for different propulsion systems depending on the split between propulsion and auxiliary power at full load

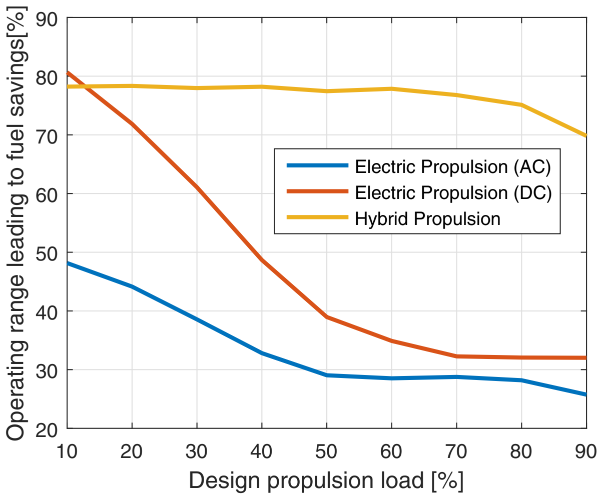

Fig. 2. Percentage of operating scenarios where fuel savings are achievable depending on the split between propulsion and auxiliary power at full load

Figure 4 shows, there can be significant variation in the relative efficiency of the configurations investigated for the same loading point. It is therefore important to consider not only the development of efficiency of both propulsion and auxiliary components at high loads and at low loads, but also the split between propulsion and auxiliary loads. Figures 5 to 7 are created using the second step described in Section II-B: the row indices represent the propulsion load, the column indices the auxiliary load and the values in the array the relative efficiency of the system. The case presented is for an even split between propulsion and auxiliary loads in the benchmark case. Note that, the split mentioned here regards the nominal load of the installed equipment, as in Figure 1.

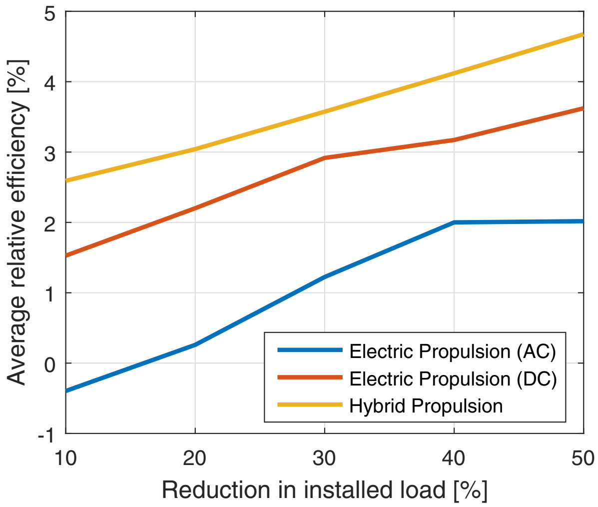

Fig. 3. Average relative efficiency for different propulsion systems depending on the reduction in maximum installed load possible (50% benchmark propulsion load at design point)

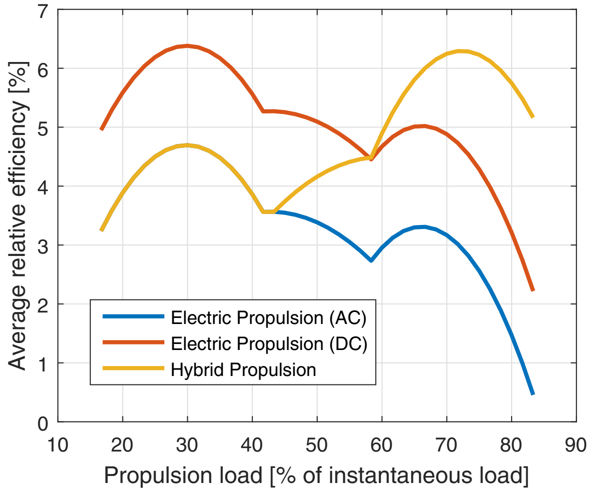

Fig. 4. Variation in relative efficiency of alternative propulsion systems for the same system loading point (30%) for different loading scenarios.

IV. DISCUSSION

A. Results Interpretation

There are two main factors determining the observed trends in the efficiency of the three modern propulsion systems: transmission losses and whether the engine is operating at constant speed. The drop in efficiency at lower loads is more pronounced if the engine is operating at constant speed. DC Electric propulsion also allows for a variation in speed and therefore improved part-load performance. However, the increased transmission losses generated by the necessary converters will still result in an overall lower efficiency if propulsion is analysed independently. This is reflected in the results by the poor relative efficiency of modern power systems

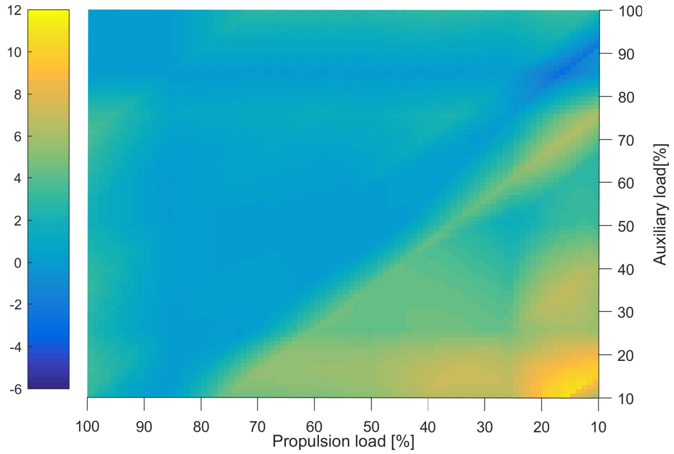

Fig. 5. Relative efficiency of hybrid propulsion for different loading scenarios (50% benchmark propulsion load at design point)

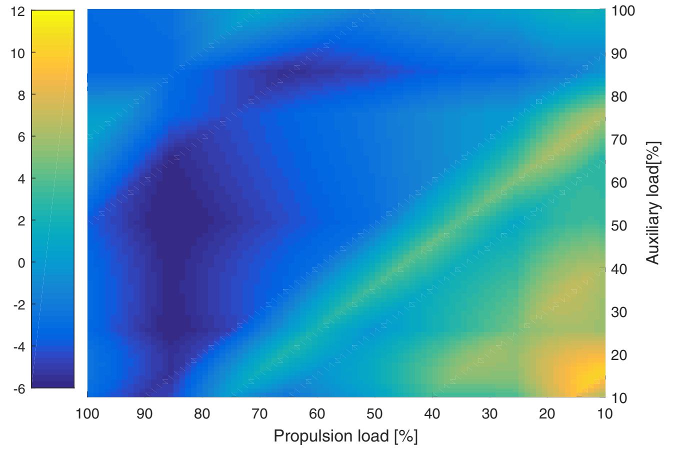

Fig. 6. Relative efficiency of AC electric propulsion for different loading scenarios (50% benchmark propulsion load at design point)

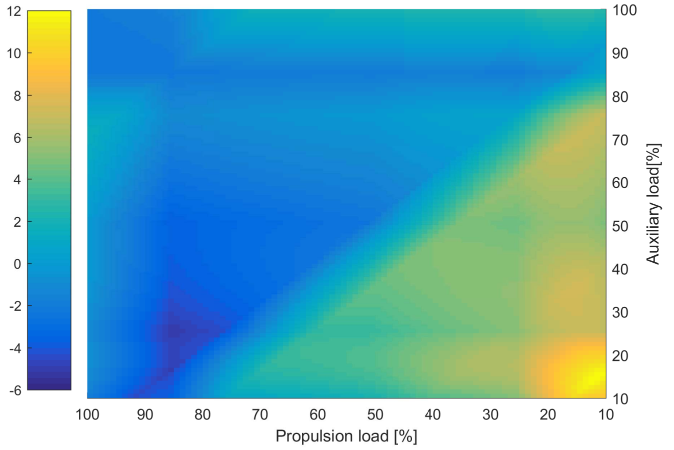

Fig. 7. Relative efficiency of DC electric propulsion for different loading scenarios (50% benchmark propulsion load at design point)

for ships where the power demand is overwhelmingly coming from propulsion (e.g. cargo vessels).

The situation changes considerably if a significant portion of the power demand is comprised of electrical loads. Not only are the transmission penalties relative to the benchmark lower (as they only differ for the propulsion load), but load sharing allows the diesel engines to run at more efficient (higher) loading points.This holds true for both design and instantaneous loads. The asymmetry along the main diagonal in Figures 5 to 7 comes from the higher efficiency of the benchmark for propulsion loads. The asymmetry along the minor diagonal is more pronounced and comes from the advantages of load sharing at low loads.

In short, the trade-off is between the increased transmission losses and the higher part-load specific fuel consumption associated with constant speed operation and the possibility of load sharing. Having a fully integrated grid enables not only a potential decrease in the total installed power but also the implementation of advanced control algorithms which ensure the optimum loading of the engines.

The differences in efficiency between the three main categories of modern on-board power systems can be seen most clearly in Figures 5 to 7. Note however that efficiency was the only factor considered. For these figures the auxiliary loads are equal to the propulsion load. Even for this theoretically favourable case, electrical propulsion has a lower relative efficiency than the benchmark for a considerable portion of the operational profile. Hybrid propulsion, on the other hand, shows a much milder asymmetry along the minor axis and might therefore be the safest choice if very little information on the operational profile is available.

B. Method Limitations

There are four major considerations missing from the approach, which should be added in later design stages: variable number of propulsion engines/generator sets, control strategy, type of auxiliary consumers and energy storage. Due to mechanical limitations, no more than two engines can be used with mechanical propulsion for one propeller shaft. Modern systems allow for an increases number of engines which can lead to a higher system efficiency by turning some of the engines off and running the remaining engines at higher loads. While the core of this effect was included (for the modern systems one of the engines was switched off at low loads), the results will not scale well if more than four generator sets are considered. This factor also introduces complexities in the control strategy used. In other words, the advantages of modern systems may in practice be higher than the values presented. The specific requirements of different consumers may affect the relative performance of AC and DC grids (through adjusted transmission losses). Lastly, the additional advantages obtainable by adding energy storage will be investigated in future work.

V. CONCLUSION

As electric and hybrid on-board power systems are improving, they are becoming a viable alternative for more and more ships. However, the decision of whether to investigate such a system or not is done in the early stages of design when very little data is available. The following conclusions, drawn from the present work, provide further information for this critical design stage.

1) For some applications modern on-board power systems can be less efficient than the traditional mechanical propulsion and separate electrical system.
2) A higher proportion of auxiliary loads leads to higher fuel saving potential of integrated on-board power systems and a higher operating range in which they can be achieved.
3) At least an approximate operational profile is necessary in order to determine whether modern power systems can lead to fuel savings for a specific ship.
4) Considering modern power systems,the highest fuel savings can be achieved during operating scenarios characterized by low loads and high relative auxiliary loads.

While some general conclusions about the relative efficiency of electrical and hybrid systems can be drawn from the present work, we consider it's main value to be as a generic tool which can be easily applied to individual cases. For example, the relative split between propulsion and auxiliary loads is known very early in the design stage. Just with this information, Figures 5 to 7 can be re-generated for the given case. Even if a more detailed operational profile is unknown, the information provides valuable decision support for the further investigation of certain types of power systems: the generic "low loads" where improvements are possible, can be replaced with a more concrete range.

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