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Energy Procedia 158 (2019) 2954–2959

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Design of a Hybrid Propulsion Architecture for Midsize Boats

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Abstract

This paper presents preliminary evaluations on the design of hybrid propulsion architectures related to midsize boats. The analysis is carried out for the case study of a retrofit operation proposed for an oceanographic ship, which is used by the researchers of the National Research Council of Italy for experimental campaigns in the Mediterranean Sea. Starting from the information obtained on the existing architecture by means of various on-board inspections, an experimental set-up is proposed for the monitoring and acquisition of the main electrical and mechanical parameters of the ship, during her navigation campaigns. Different possible hybrid configurations are also proposed, identifying the main advantages and drawbacks of each configuration for the considered application. The proposed set-up allows obtaining experimental information, about the behaviour of the ship in a large variety of operative conditions, which will be useful to support the choice of a proper hybrid propulsion architecture and the optimal design of components.

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Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.

Keywords: hybrid ship; marine propulsion architecture; marine energy generation systems

1. Introduction

Emissions of exhaust gases and particles from ships represent a significant contribution to the total emissions from transportation sector. In fact, although several technologies can be used as prime movers (e.g. diesel engines, gas and steam turbines etc..) for ships, all of these options are based on the conversion of chemical to thermal and mechanical energy by means of combustion processes. As well known, these processes generate a large amount of

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Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.
10.1016/j.egypro.2019.01.958

exhaust emissions, mainly in terms of CO_2, SO_X, NO_X and particulate matter, which are strictly related to the engine technology, the fuel quality and the combustion process itself [1]. On the other hand, the global economy strongly relies on the shipping industry, as it is in charge of moving about the 90 % in weight of traded goods. As a consequence, in line with the rising number of ships both in private and in corporate sector, a relevant increase in marine diesel oil (MDO) consumption has been recently observed.

The above considerations have encouraged the development of new legislations, which introduce strong limitations and penalties with the aim of reducing exhaust emissions in the marine sector [2]. On the other hand, the application of environmental restrictions and high efficiency requirements are limited by the very low penetration level of new technologies in the marine industry, which is still considered as a conservative sector. In fact, traditional diesel propulsion systems are generally based on old technologies and are designed on the basis of the maximum power demanding operations for the considered ship. Unfortunately, the ship generally operates in these conditions just for few hours, in comparison with her daily mission. As a consequence, diesel engines often results oversized and are forced to work in low efficiency/high emissions operating points [3]. In this context, the use of electric propulsion systems in hybrid configuration with traditional thermal engines could be considered, both for the design of new ships and for retrofit operations, as an attractive solution to reduce fuel consumption and exhaust emissions. In fact, as well known, electric drives present a large number of advantages in terms of conversion efficiency, ship manoeuvrability, reliability, safety etc. [4]. Various applications related to electric and hybrid vessels, with different missions and sizes, are reported in literature. These applications generally refer to optimal design of specific prototypes based on innovative propulsion and energy generation technologies [5]-[7]. On the other hand, the recent needs to adapt old vessels to the efficiency requirements of new legislations has encouraged the growing interest of researchers and technicians towards the hybridization of existing vessels through retrofit operations.

In this context, the aim of this paper is to carry out evaluations for the hybridization of an existing ship, starting from an analysis of her existing thermal configuration and operative conditions. With this aim, this paper firstly analyses the considered case study with a description of its propulsion and on board electric generation architecture. Then a measurement and acquisition system is described and proposed, in order to perform preliminary analysis of the ship performance in her existing configuration. Finally, different architectures are considered for the integration of electric drive and generation systems to support the hybridization of the considered propulsion architecture.

2. Case study and existing propulsion Architecture

The evaluations reported in this paper are referred to the case study of a mid-size ship called G. Dallaporta, with a length overall of about 30 meters, which is used by the researchers of the National Research Council of Italy in order to carry out experimental oceanographic campaigns. Theoretical considerations about the main requirements for the hybridization of this ship have been already described in a previous paper published by the authors [8].

The existing propulsion architecture of the considered ship is based on a Wärtsilä 810 kW diesel engine, connected to a transmission gear, which works as prime mover for both a variable pitch propeller and a 78 kW shaft electric generator. A hydraulic pump is connected to the diesel engine to supply ancillary services through the on-board hydraulic circuits. The ship is also equipped with an additional diesel gen-set Caterpillar 170 kVA, which supplies hydraulic and electric auxiliary services, when the diesel engine is switched off. In this regard, Fig. 1 shows pictures of the diesel engine and of the gen-set, which have been taken during a preliminary inspection on-board.

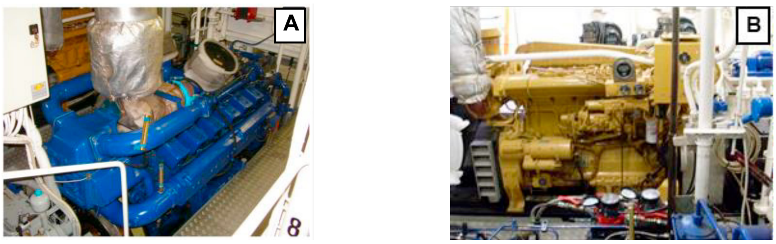

Fig. 1. On board pictures of thermal engine (A) and Diesel gen-set (B).

The hybridization of this kind of architecture could involve different benefits for the overall propulsion system efficiency. In fact, the great part of ship operating conditions (e.g. manoeuvre or low/medium speed navigation) are generally performed with very low power requirements for the diesel engine. These operations are far from the diesel engine optimal operating points and involves high specific fuel consumptions with the related increased levels of pollutant exhaust emissions. Investigations through measurement campaigns are required, to obtain useful preliminary information on the behaviour of the existing propulsion system in different operative conditions.

3. Procedures for monitoring and evaluating propulsion system performance

All the on-board loads of a midsize boat are supplied by the main engine and can be grouped in mechanical, electric and hydraulic loads. The propulsion system, which is devoted to propel the boat at the desired speed, is generally the most power demanding load [9]. However, according to the mission of the boat, electric or hydraulic loads, such as electric pumps, winches and hydraulic pumps for cranes, can be energy demanding as well. The performance of this propulsion system can be defined as a function of a high number of parameters, which should be simultaneously monitored in order to obtain consistent information on energy demand and efficiency.

Monitoring sensors

Two volumetric sensors have been used to evaluate the fuel consumption in l/h, $FC(t)$, as the difference between the fuel entering, $F_{in}(t)$, and returning, $F_{out}(t)$, in/from the engine, on the basis of equation $FC(t)=F_{in}(t)-F_{out}(t)$ [10]. As shown in Fig. 2, the volumetric fuel flow meters are installed within the mechanical sensors, where a couple of gears are moved by the flow entering the sensor chamber and at each complete rotation of the gears an electric signal is provided by the embedded PCB, which represents a constant calibrated unit of volume. The physical measurement is thus a frequency of pulses, which is directly related to the flow in volume per unit of time. Flow sensors commonly adopted are volumetric sensors with a flow range from 10 to 500 l/h and an accuracy of 0.25%. These sensors are also able to compensate the effects of temperature variation on flow measurement.

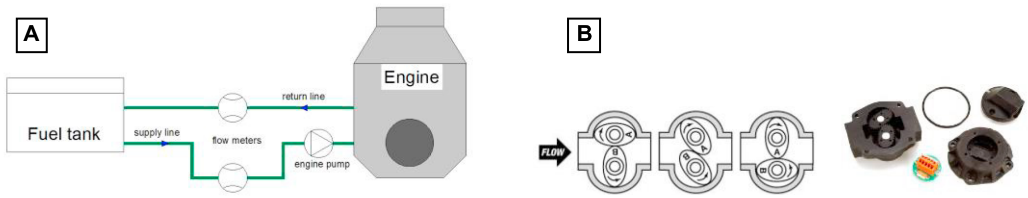

Fig. 2. (A) fuel consumption monitoring system. (B) Volumetric flow sensors used for monitoring the fuel consumption of the vessel.

In order to evaluate the propeller power, a torque meter is installed on the intermediate shaft, between the reduction gearbox and the stern tube [11]. The torque measurement is carried out by measuring the deformation of the shaft surface. Two optical rings, supporting optical sensors sensible to the shaft surface deformation, are clamped on the shaft at a fixed distance as shown in Fig. 3 A. The torsion of the shaft is transmitted to the rings and the torque is measured as a function of the frequency change of vibrating strings. This approach allows an immediate installation of the sensors, avoiding a stop of the boat and any change on the intermediate shaft. The common measurement range is from 1000 to 18000 Nm. The rotational speed of the shaft is measured through an optical counter, which is shown in Fig. 3 B.

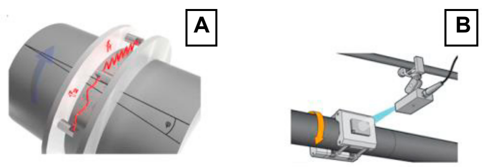

Fig. 3. Monitoring system for the propulsion power: torque (A) and speed meter (B).

The power, P_D, in kW delivered to the propeller can be easily calculated, as a function of the torque, M, in kNm and of the shaft revolution speed, rpm, with equation $P_D=M\cdot rpm$.

The electric power supplied by the shaft generator is measured through ammeter clamps, connected to the main phases of the electric generator. On the basis of the measured current values, $I_{1,2}$, and the electric grid voltage, V, the electric power in kW, P_{EL}, can be calculated with the equation $P_{EL}=avg(I_1,I_2)\cdot\sqrt{3}\cdot V\cdot 10^{-3}$.

Hydraulic pumps, coupled with the main engine, drive all the hydraulic users such as winches, cranes high-power oleo-dynamic loads. The power adsorbed by hydraulic pumps is evaluated by measuring the flow and pressure of the hydraulic oil immediately after the pump, trough the measuring system reported in Fig. 4. In particular, the flow of hydraulic oil, F_{OL}, is measured in m^3/h with a turbine that is moved by this flow, whereas its pressure, p, is evaluated in N/m^2 through a piezo metric pressure sensor. The hydraulic power in kW, P_{OL}, is calculated as $P_{OL}=p \cdot F_{OL}$.

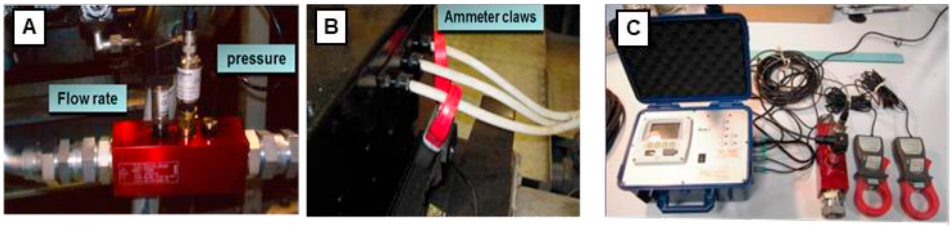

Fig. 4. Hydraulic power measurement (A), ammeter claws for measuring current of electric generator (B), data recording system (C).

A gas analyser is adopted for the evaluation of quantity and composition of the exhaust gases from the main engine. Flow and temperature of the exhaust gases are also measured with a thermal sensor that controls the instantaneous temperature and its gradient. Values of SO_X, NO_X, CO, CO_2, particulate, H_2O, temperature of the exhaust gases analysed are measured in terms of ppm on a unit of gas volume.

The speed, course, position of the vessel can be recorded by a GPS antenna. GPS data are generally provided through a standard NMEA sentence and can be recorded through a RS232 serial port with a baud rate of 4800. The role of the GPS is essential also to assign the synchronization time stamp to all the sensors on board.

Data management system

Data collected from the sensors are managed through a control unit that synchronizes, checks and validates the raw data. The control unit is configured with a specific software composed of different modules [12], one per each sensor installed, that are in charge of the independent control of the sensor. The validation process aims to exclude outliers and other inconsistencies following a procedure based on the definition of restricted variability ranges. Data included in the preliminary validation are organized in a MySql database, for the analysis. Data validated are organized in datasets with a time rate of one minute. Each parameter is averaged at 1 minute and synchronized. The complete scheme of data collection, management and analysis is reported in Fig. 5.

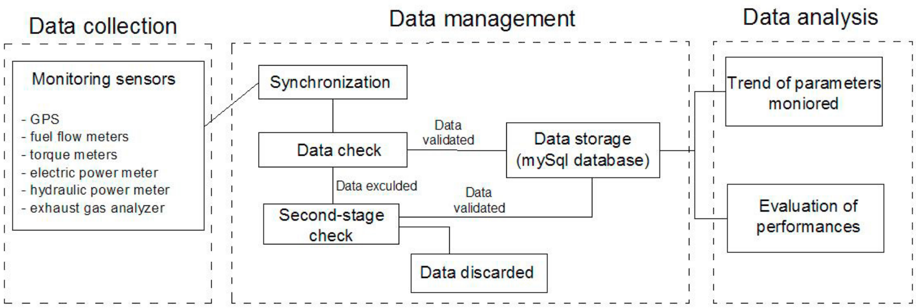

Fig. 5. Data collecion, management and analysis architcture.

Performance definition of a propulsion system is challenging due to the difficulty in defining some boundary layers such as the sea and wind, the motion of the boat, etc.. In order to take into account these issues on board measures are generally performed with redundancy and repetitions of specific tests at sea.

Data analysis

As shown in the above Fig. 5, performance evaluations of the propulsion systems are based on the trends of singles parameters (fuel consumption, vessel speed, power delivered, electric power demand, etc.). As well known, the above trends and performances are influenced also by the operative profile of the vessel. For this reason, as first step for data analysis, an example of vessel operative profile is defined in order to compare results with similar profiles. In Fig. 6 the propulsion system power (A) is represented in terms of temporal trend and frequency distribution, reporting a sample of two different working profiles.

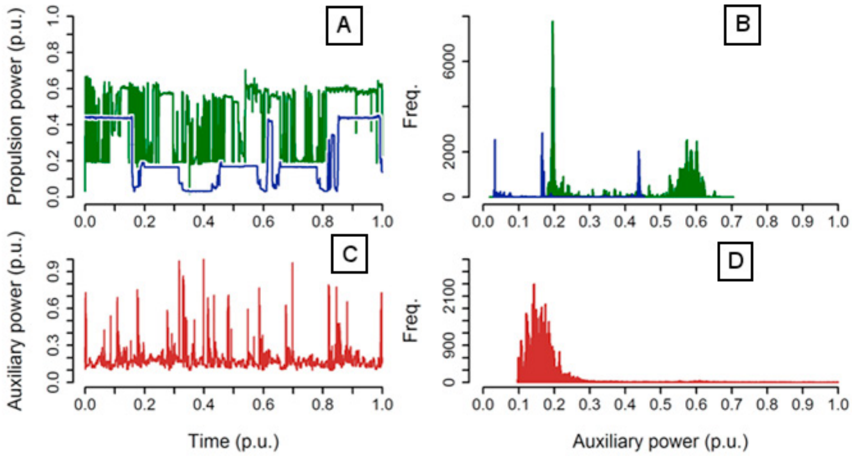

Fig. 6. Evaluation of trend and performance of the propulsion system.

The power demand of the propulsion system (A) is compared for two different working profiles. In this case, the most power demanding operations are related to the cruising phases. The profile represented in blue is a sample of a sea trials regarding fishing technology experiments, which is characterized by three different modes, reported in the histogram (B), related to cruising from/to fishing grounds (42% of the maximum power), fishing activity (20% of the maximum power), and the lowest, describing manoeuvring between different cruising/fishing phases. The sum of hydraulic and electric power of auxiliaries is shown in Fig. 6 C. Such power demand is similar for different profiles and the histogram analysis shows that the great part of requested values is between 10 and 25% (D).

The considered set-up allows to obtain experimental results, which are useful to support the proper choice and design of a hybrid propulsion architecture for the considered case study.

4. Proposed Hybrid Architecture

A hybrid architecture can be designed, starting from the measures obtained during experimental campaigns through the above described procedures. In this regard, different propulsion schemes can be evaluated for the hybridization of the considered ship. In particular, simple diesel-electric configurations are already conveniently used for large size ship, where the electric power required by the on-board ancillary and hotel services is comparable with the electric power required by the propulsion system. In fact, in these cases, fast transients in electric motor power demand do not affect the performance of the diesel engines which continues to work as a generator in optimized operative conditions.

A series hybrid architecture, with the electric motor supplied by a diesel gen-set and a battery pack, could be more suitable for a mid-size ship. In fact, in this case, transient phases of the electric drive can be supplied with the contribution of the battery pack with the thermal engine working in optimized operative conditions. Unfortunately, with this configuration the electric drive works as a prime mover and, for this reason, it needs to be sized on the basis of the overall propulsion power with negative effects on costs, weight and space.

As a consequence, the hybrid parallel architecture, where the mechanical energy required for the propulsion is simultaneously transmitted to the propeller from both the electric motor and the thermal engine, is generally preferred for mid-size ship. With this configuration, also retrofit operations can be performed, as it allows the addiction of a new electric drive maintaining the same diesel engine, with evident advantages in terms of costs. In this regard, retrofit operations for the considered ship can be carried out on the basis of two different architectures, which are schematically reported in Fig. 7. The first scheme considers the installation of a new gear box, which presents an additional PTI for the connection of the electric drive. This scheme is characterized by the advantage of simplifying the installation procedure, which requires either the change or the upgrade of the existing gearbox, without further interruptions in the transmission lines. In the second scheme, both propulsion units are connected on the same shaft by means of an electrohydraulic clutch, which can be controlled in order to allow the selection of the desired propulsion/energy generation mode, by including or excluding the contribution of the electric motor/generator in the propulsion chain.

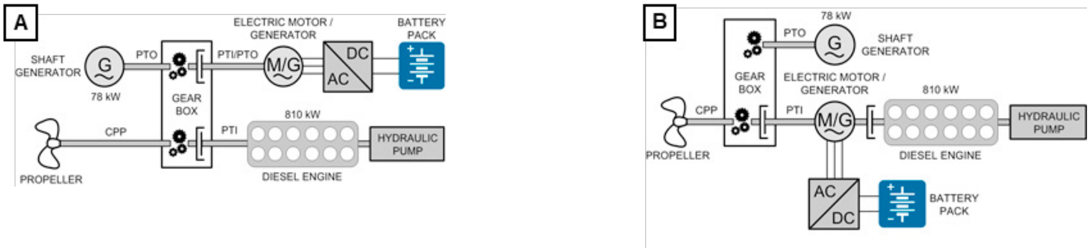

Fig. 7 Hybrid parallel thermal electric architectures.

For both the above configurations, an additional battery pack has to be considered in order to supply the electric drive. The integration of the battery pack can be performed through properly controlled IGBT AC/DC power converters, which allows the battery pack to supply the electric drive during the electric navigation mode, and to be recharged with the energy coming from the diesel engine during the energy/generation mode.

5. Conclusions

In this paper, preliminary evaluations for the hybridization of a mid-size ship are presented. In particular, a retrofit operation has been proposed for the case study of an oceanographic ship of the National Research Council of Italy. Starting from an analysis of the existing propulsion architecture, the set-up of an experimental monitoring and acquisition system for mechanical and electric parameters of the ship has been proposed and described. In addition, different configurations of hybrid architecture for marine applications are analysed with details on their main advantages and drawbacks. In conclusion, this manuscript represents a further step to carry out the complex engineering procedures, required to complete the hybridization of a midsize ship, through retrofit operations.

6. Acknowledgements

The authors gratefully acknowledge Mr. Antonio Rossi and Mr. Salvatore Gabriele, who work as technicians of Istituto Motori, for their cooperation in drawing the figure of this paper.

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