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Real-Time model-based design for CODLAG propulsion control strategies

M. Martelli*, M. Figari

Department of Electrical, Electronic, Telecommunications Engineering and Naval Architecture (DITEN), University of Genova, Italy

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ABSTRACT

Design and optimization of propulsion control strategies is a crucial part of ship design. In fact, propulsion plant behaviour is greatly influenced by the control system dynamics. Acceleration, deceleration, crash stop, heavy turning are some examples of transient conditions that a propulsion plant has to sustain whilst maintaining optimal performance without reducing ship safety and reliability. In this paper, the methodology and the simulation models needed to design the propulsion control logics for an innovative CODLAG propulsion plant are discussed. The methodology is based on the RT-HIL already used by the authors in a previous naval ship project and consists in the development of the propulsion control logics in a virtual environment. In order to increase the reliability of the results new and more detailed ship simulation models have been developed and their validation discussed in the paper. Thanks to this methodology, it is possible to test the control system under different operational conditions off-line, ashore in the office, without any hazards for the real system. The overall design time is reduced and this allows reduction in the time and the related cost of the sea trials for the final commissioning. At the end of this paper, sea trials results are shown to demonstrate the effectiveness of the proposed approach.

1. Introduction

The capability for efficient use of the power necessary to perform the required tasks within the boundary conditions imposed by machinery or environment constraints is one of the primary tasks of the propulsion control system. To achieve this goal, the propulsion control logics have to be designed and tested for a wide range of foreseeable ship operations. A modern and efficient way to develop the control design is to first develop it in a virtual environment and then translate the control logics into real hardware (PLC). In order to achieve the desired full-scale performance before the ship availability the PLC, linked to the virtual model of the ship, can be tested in detail and optimised by Real Time Hardware in the Loop techniques.

The above-mentioned approach has demonstrated its technical and economical effectiveness for the design of marine systems especially when no experience exists (see Altosole et al., 2007; Johansen and Sorensen, 2009; Michetti et al., 2010). The main aim of the paper is to present and discuss the methodology adopted for the development and the validation of the control strategies for an innovative CODLAG propulsion plant.

With respect to previous authors' experience and state of the art literature, the main innovation is the highly nonlinear ship propulsion simulator able to run in real time. The objective of the proposed simulation approach is to adequately describe global ship behaviour by modelling ship manoeuvrability, the propulsion plant and the control system in one simulation platform containing mutual interaction terms (system of systems approach). This complex modelling allows realistic ship systems feedback otherwise unavailable with standard simulation techniques.

The ship and machineries mathematical models used in this work are fully validated by Martelli et al. (2014a, 2014b), where the fidelity and completeness of the several mathematical sub models have been proved.

In the last few years, ship propulsion systems have experienced major innovations to meet the needs of the ship owner, to satisfy the mandatory rules in term of safety and environmental impacts and to reduce fuel oil consumption. The increasing complexity of these new marine propulsion systems, such as the COmbined Diesel-eLectric And Gas (CODLAG) objective of this study, includes different engine types with very different power and rotational speeds. This necessarily leads to the development of dedicated propulsion control strategies. The propulsion control should be designed to manage such a complex system in a safe and economic manner, in all foreseeable conditions. Furthermore, the propulsion control systems should also be able to ensure the best performance of the propulsion plant in all conditions; in the proposed case study, 13 different operational modes have been analysed, including "boost" condition where gas turbine and electric motor together provide the necessary torque on the same shaft.

* Correspondence to: Via Montallegro 1, 16145 Genova, Italy.
E-mail address: michele.martelli@unige.it (M. Martelli).

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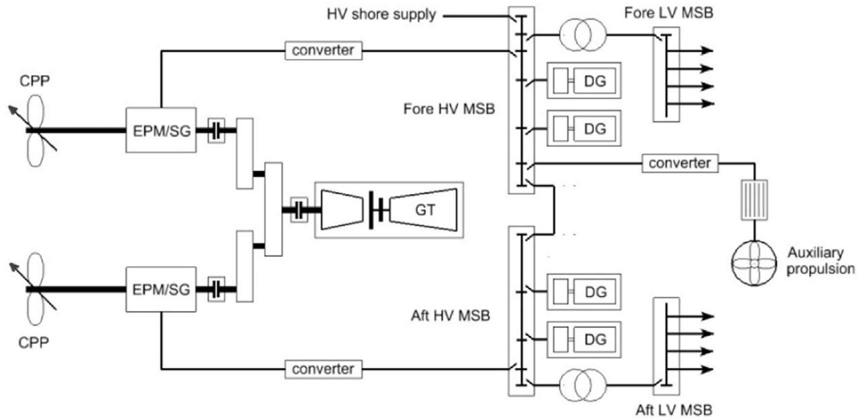

Fig. 1. Propulsion Plant Layout.

In open literature, several works dealing with marine simulation topics are present. In particular, three comprehensive books has been wrtitten by Fossen, (1994, 2002, 2011) regarding the equations of motion and propulsion control simulation for ocean vehicles. These works are very detailed as far as control system and vehicle hydrodynamics simulation, while the propulsion system is often absent or simplified. Specific papers dealing with propulsion plant topics: the main engines, auxiliary systems can be found in some works (see Rubis, 1978; Rana et al., 1997; Benvenuto and Campora, 2005; Altosole et al., 2014), and of particular note, the works of Rana and Rubis also deal with the turbine control system. Diesel engine simulation models used for ship propulsion control design can be found in (Schulten and Stapersma, 2003; Benvenuto and Campora, 2007; Baldi et al., 2015).

Propeller pitch change mechanisms have been thoroughly studied in several works (see Bakker et al., 2006; Wessenlink et al., 2006; Godjevac et al., 2009; Martelli et al., 2014b) from the point of view of mechanics, hydraulic systems, and acting loads. The literature regarding ship manoeuvrability simulation is too vast to be reviewed in a few words, thus we address only a few authors whose works have been used in the present paper. In particular, in some papers (see Ankudinov et al., 1993) a modular mathematical approach for real time manoeuvring in three degrees of freedom is proposed; instead the roll motion during turn is studied by Kijima and Furukawa (1998); a comprensive book dealing with manoeuvring technical problems has been proposed by Brix (1993); Viviani et al., (2007, 2009) addressed the ship manoeuvre capability taking into account the shaft line unbalance; this last effect is very important from the controller designer point of view, as will be explained in the following sections of the paper.

Weather conditions such as wind and current effects on ship behaviour, are also simulated by Altosole et al. (2013).

Ship modelling with an holistic vision of the “ship systems” is becoming more common. Some studies on ship simulation, including propulsion plant, manoeuvring models, and control systems are reported in literature (see Bodnaruk and Rubis, 1971; Schulten and Stapersma, 2007; Martelli, 2015).

Regarding the ship controller, several works (see Amy et al., 1997; Johansen and Sorensen, 2009; Stapersma et al., 2009; Geertsma et al., 2017) deal with propulsion controller design through massive use of simulation techniques and real time hardware in the loop testbed.

Regarding the CODLAG controller, due to the novelty of this kind of propulsion system, no works are present in open literature.

The paper first introduces the complexity of the CODLAG concept and its control challenges. Second, the paper briefly describes the mathematical approach as a “system of systems”, fully developed in the referenced papers.

Then the paper shows the engineering implementation of the presented approach, a software platform that allows the study of the vessel's dynamic behaviour during transient conditions (acceleration, deceleration, etc) and during steady state conditions (constant speed navigation) as well as analysis of the mutual interaction between all the elements involved, suited to run in real time and in batch mode. Particular attention has been paid to the choice and the development of system physical models, able to achieve both high fidelity and reasonable computation time. With respect to previous works, new detailed models of the CPP mechanism have been introduced, the hull dynamics is treated as a 6 DOF problem, and all the different control layers (ship supervisor and local controllers) have been modelled.

Section 3 discusses the development and the tests of the new propulsion control strategies where no previous experience exists.

At the end of the paper a comparison between simulation results and data acquired during a sea trial campaign of the first ship of the class, is shown and discussed.

2. Propulsion control system overview

Fig. 1 shows the general architecture of a particular ship propulsion, a COmbined Diesel eLectric And Gas (CODLAG) plant, where a gas turbine (GT) drives two controllable pitch propellers through a cross-connected gearbox. Two electrical propulsion motors (EPMs), directly mounted on the shaft lines, can be used for low speeds during the silent running or together with the gas turbine for full power. Four diesel generators provide the electric energy. Such a complex plant enables several propulsion modes; about fifteen. Each mode has specific overall performance requirements to be achieved within the performance envelope of each component.

An example of an overall requirement is ship acceleration or ship stopping ability; an example of component performance envelope is the maximum torque unbalance between the two shaft lines to preserve the wheels’ teeth of the cross connected gearbox. The ship supervisor system, or ship control system, provides Human Machine Interface (HMI) capabilities as well as systems control. The ship supervisor is divided into different sub-systems, Fig. 2, each manages and controls different on-board activities: ship safety, propulsion, electric power management, etc. The focus of this work is the design of the particular characteristics of the propulsion control system.

The crew can interact with the propulsion machineries through the different operator stations (OS), linked to each other by a LAN that forms the control network. The automation servers, through the I/O device, link the control and the field bus networks. These elements transform the human action (the movement of a lever, the touch of a screen) into an actual signal to the Programmable Logic Controllers (PLCs). In addition, incoming field information is stored in these servers. All the PLCs and the sensor need to manage the different systems composing the field bus network. In this network PLCs receive