Advances in automation design for fast vessels propulsion

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ABSTRACT: Superior performance, flexibility and energy efficiency, make more and more important the automation role in marine propulsion applications. Controller hardware and software should be designed for safe operation in all conditions, as well as for high dynamic performance. The increasing complexity of the actual marine propulsion systems leads to the development of dedicated control functions, according to special requirements. In order to test performance and reliability of the propulsion control logics, new design approaches for the marine automation design should be introduced. With regard to this, the “Real Time Hardware in the Loop” (RT HIL) simulation technique is becoming a standard part of the design process for the propulsion controller of the last and most important Italian naval vessels.

This paper deals with some new solutions in automation design, from the RT HIL simulation benefits to the introduction of special control aspects, due to the need to manage high power engines for different propulsion conditions. In particular, the general propulsion automation schemes, analysed in this paper and proposed for high powered fast ships, are the results of the experience gained by the authors during the cooperation between Genoa University and the Italian automation provider “Seastema S.p.A”, for the propulsion controllers designs of the aircraft carrier Cavour (COGAG propulsion) and FREMM Class frigates (CODLAG propulsion).

1 INTRODUCTION

The increasing demand for a fast and economical marine transport of passengers and freights is giving renewed boost to several innovations and developments which will set the new standards for the next marine propulsion applications. The new propulsion systems are designed to meet the needs of both commercial ships and high powered naval vessels, in order to satisfy the growing demand for higher speeds. In particular, in recent years, more and more powerful marine gas turbines, often combined with the well known advantages of electrical propulsion (CODLAG or CODLOG systems), have been fully exploited by many of the world’s navies. New target power levels have been planned to magnitudes which were unthinkable up to a few years ago. The increasing complexity of these new marine propulsion systems leads necessarily to the development of dedicated control functions, able to manage such high power levels in a safe way and for different propulsion conditions of the vessel.

In order to test performance and reliability of the propulsion control logics, new design approaches for the automation development have been recently introduced: for instance, the “Real Time Hardware in the Loop” (RT HIL) simulation technique is becoming a standard part of the design process for the propulsion controller of the new Italian naval vessels. According to this design approach, the propulsion system is simulated by a numerical code which is linked in real time to the real hardware (the CPU that controls the ship propulsion system), providing to the designer a realistic feedback before the installation on board of the real control system.

Regarding other advances in automation design for fast vessels, a brief overview of the most interesting control functions for recent COGAG and CODLAG applications will be presented in this paper. The general schemes of propulsion automation, shown hereinafter, are the results of the experience gained by the authors during the last two cooperations between Genoa University and Seastema S.p.A. for
the design of the propulsion control systems of the aircraft carrier Cavour and FREMM Class frigates.

2 SIMULATION BASED DESIGN

2.1 Prototyping system.

During the simulation based preliminary design, it is proper that simulation runs in batch mode, in order to achieve all the calculated data in the faster time (that means a test of 60 seconds, for example, is simulated by PC in less than 60 seconds). The calculation time depends on several factors regarding both some hardware solutions (computer memory, CPU speed) and the developed numerical model (simulation time step, stiffness, kind of solver for the ordinary differential equations). In this phase, the control logic can be designed and the several gains of the regulation loops can be set in an ideal system, representing the interaction between two software-only simulation models (control system and ship), as it is illustrated in Fig.1.

Figure 1. Data exchange between control and ship simulator

2.2 Control system onboard.

A typical architecture of the propulsion control system of a ship could be the following:

Figure 2. Architecture of the propulsion controller

Several CPUs are usually used to control different components of the propulsion system, trying to limit the lost of functionalities in case of failure of one of them (even if each CPU is used in a redundant configuration).

Unfortunately, the behaviour of the real hardware on board could be quite different from that one simulated during the preliminary design phase. The main differences could be due to the cyclic time of the CPUs, the different time delay in exchanging data among controllers and the native functions that can be implemented; further differences could be represented by the presence of many functionalities usually not implemented in the ship numerical model (but that interact with the propulsion control) and the thousands of signals that the automation has to monitor on the real system.

In the real system, the whole control system has to work in real time and the automation designer has to be sure that the performance foreseen by simulation will also be maintained in a real environment. To this end, it is necessary to limit, as soon as possible, most of the differences between the two worlds. This could be made possible by the adoption of the RT HIL method.

2.3 RT HIL method.

Once the control logic performance has been evaluated by using batch simulation, the control subsystem is tested by RT HIL simulation. This design technique consists in test setup where the real hardware controller can exchange data with the ship propulsion models (engine, shaft line, propeller, ship motions, etc.) that are simulated in real-time (for example, a test of 60 seconds must take exactly 60 seconds to run on PC).

Generally the test of the real controller is made on shipboard, partially during the delivery period and completely during ship full scale trials. These trials are time consuming and very expensive, as they require the full ship availability. By using RT HIL simulation, the physical availability of the ship is not required, thus the controller testing can be done even before the ship is built. In order to increase the simulation realism, some functionalities, not implemented in the ship model, are simulated by codes inside the controllers.

Figure 3. Test-bed used for RT HIL trials
Fig. 3 shows the block diagram of the experimental setup used for testing the controller of the FREMM Class frigates. In particular, the file named Fremm.exe is the RT application that executes the propulsion model. It is an OPC client that reads the command parameters on the controllers, through OPC servers, and writes back the results. OPC servers and the Fremm.exe application reside on the same PC and each OPC Server exchanges data with one controller through Ethernet LAN. The “Simulated Functionalities” can interact with an HMI (Human-Machine Interface) page in order to supply commands from users (i.e. the selection of the lever position and of a precise propulsion mode) and to simulate the minor systems not implemented inside the model.

All of the parameters exchanged via OPC can be logged to a file but they are also available to the automation designer by means of a graphical panel, as illustrated in Fig. 4 and Fig. 5. In this way it is possible to have a comprehensive view of all the system working parameters.

Since the Fremm.exe application is completely configurable, it is possible to try the controller with different working scenarios (i.e. different ambient temperature, rudder angle, etc.). This is an additional advantage of the RT HIL approach: not only the designer can debug the controller before the on board delivery, but it is also able to test it in borderline situations, that can be difficult to obtain with the real ship.

3 CONTROL FUNCTIONS

3.1 COGAG application.

A modern controller layout for a COGAG application, in according to a generic propulsion system as shown in Fig. 6, could be represented by the scheme of Fig. 7, where the control logics of a single shaft is illustrated.

![Figure 6. COGAG propulsion system](image)

In the proposed scheme, the bridge lever position signal is converted into a reference value for the propeller pitch and speed by means of two combinator tables, where the steady state values for propeller pitch and speed, depending on lever position, are respectively reported. The pitch setpoint is possibly corrected to keep each engine within its torque limit during every condition, while the requested propeller speed is compared with the measured actual shaft speed to feed a PID algorithm, able to assess the GT throttle demand. This kind of speed error is adjusted on the basis of the actual GT torque, in order to take into account the possible different performance of the two engines acting on the same shaft. In reality, the final GT throttle is the minimum signal between the results achieved by two PID algorithms, which act:

1) On the shaft speed error;
2) On the difference between the torque limit (for instance equal to 85% of the GT nominal torque) and the GT actual torque.

The GT throttle signal is calculated on the basis of the torque error to prevent overloads, but as the possible correction of the pitch setpoint is made on the basis of a torque limit which is lower than the previous one (i.e. 75% of the GT nominal torque), the possible overload protection is determined firstly by the pitch reduction and then by the GT throttle reduction.
Once the GT throttle demand is calculated, the corresponding Turbine Control System (TCS) has to regulate the fuel flow in order to achieve the proper power required by the propeller (Altosole et al. 2010a).

The propulsion controller is developed in order to prevent the intervention of the inner governor of the engines. In fact, in this control logic, the protection functions of the engines’ local governors have to act only as the last tool to avoid overtorque, overspeed or overtemperature of the propulsive machinery during transient or emergency conditions.

At the end, the main functions of the considered controller can be so resumed:

- calculation of propeller speed and pitch setpoints, by using auto-adaptable ramps based on ship speed (blocks 1 and 2 in Fig. 7);
- engine throttle calculation, mainly on the basis of the shaft speed control;
- overload protection, by acting on the propeller pitch, in order to avoid engine torque peaks;
- torque balancing of the two gas turbines acting on the same shaft.

### 3.2 CODLAG application

The complexity of this recent and innovative CODLAG system (whose possible configuration is shown in Fig. 8) requires the development of a propulsion controller able to perform several and dedicated functions to safely manage the various propulsive modes of the vessel.

Also in this case, the control design criterion is to prevent the intervention of the Turbine Control System (TCS) and the inner governor of the electric motor.

In the GT mode, the controller layout similar to that of a CODAG system (see Fig. 9).
The control scheme, proposed for both cases in the GT mode, is illustrated in Fig. 10. The bridge lever position signal, modulated by auto-adaptive ramps based on the ship speed demand (blocks 1 and 2), is converted into a propeller blade position and shaft speed reference value by means of the combinator tables. The requested propeller speed is then compared with the measured shaft speed and the corresponding error feeds compensating algorithms (PID block) in order to calculate the throttle demand of the gas turbine or the electric motor, respectively for the GT mode and EPM mode. Moreover a specific control loop, acting firstly on the propeller pitch and secondly, if necessary, on the GT fuel flow, is added to this kind of regulation in order to maintain the gas turbine or the electric motors within their torque limits during every operational condition. In particular, the final GT signal, which feeds the TCS, is calculated as the minimum signal among three signals achieved by the following actions:

- shaft speed regulation (signal calculated by a PID algorithm, on the basis of the shaft speed error);
- GT torque protection (signal calculated by a PID algorithm, on the basis of the error between the GT torque limit and the GT actual torque);
- shaft torque protection (signal calculated by a PID algorithm, on the basis of the error between the shaft torque limit and the shaft actual torque).

The normal regulation based on the shaft speed is usually adopted by many marine control systems but the most delicate point, that makes different this propulsion control system from the other traditional controllers, regards the particular type of the used gearbox, characterised by two output shafts. In fact, for this reason, the normal regulation of the engines, based on the shaft speed, is not proper for the CODLAG mode, i.e. when the overall controller has to calculate the signals to send to both the GT and the two EPMs, because in this propulsive configuration it would be improbable to achieve simultaneously for the two shafts the same exact feedback, regarding the propeller speed, during transient conditions. Therefore, in CODLAG mode, the EPM regulation is only based on a power reference that takes over when the GT throttle demand exceeds for example the 85% (Altosole et al. 2010b).

Moreover, the particular reduction gear arrangement can suggest to introduce into the control logics a further capability, in order to preserve the teeth of the gears from torque unbalances during critical turning circles of the vessel. As it is well known, ships during manoeuvres can experience large fluctuations of the required shaft power, especially in the case of very tight turning circles at the maximum rudder angles; these fluctuations can lead to a considerable increase of the shaft power, or shaft torque if propeller revolutions are kept constant, up to and over 100% of the steady values in a straight course. Moreover, during a tight turning circle of a twinscrew ship, the torque fluctuations of

![Figure 10. Controller layout for CODAG/CODLAG applications](image-url)
the two shafts can be significantly different, if compared between them (Altosole et al. 2008). These effects could be potentially dangerous, if not correctly predicted and cared for, in case of some particular kinds of propulsion plant, in which for instance two shafts are powered by the same prime mover via a unique reduction gear, like in the considered CODLAG system but also for CODAG systems (see Fig. 9). For this reason, it was decided to implement in the controller layout also a specific function able to cancel significant torque unbalances of the two shafts, by properly acting on each propeller pitch (in Fig. 10 this particular function is represented by the block “pitch adjustment”).

4 CONCLUDING REMARKS

In this paper, several aspects regarding automation design procedures and particular control functions are discussed. RT HIL simulation is a design approach already used since several years for automotive control systems and recently introduced by Seastema S.p.A. also for naval applications, by using mathematical models developed at Genoa University. By means of this powerful technique, it is possible to plan and test new propulsion control solutions for more and more complex propulsion systems, able to manage high power engines, as marine gas turbines, for different propulsion conditions.

On the basis of the control schemes discussed in this paper, a modern marine propulsion control for fast vessel application should be characterised by the following capabilities:

- Traditional shaft speed regulation in standard conditions;
- Proper auto-adaptive ramps, depending on ship speed demand and acting on the telegraph signal, in order to provide soft dynamics for the propulsion machinery;
- Overtorque protections for shaftlines and engines, based on both pitch propeller adjustment and fuel throttle reduction;
- Torque balance functions to assure the same performance of the engines acting on the same shaft;
- Shaft torque balance functions in case of particular gearboxes having two outputs, as in the recent CODLAG or CODAG applications.

In general, the first three functions should provide superior performance, flexibility and energy efficiency of the propulsion system, while the last two should help a good level of maintenance of the machinery on board.

5 REFERENCES