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Propulsion control strategies for ship emergency manoeuvres

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ABSTRACT

This work deals with the propulsion control aspects relating to some of the most critical emergency manoeuvres of a ship: slam start and crash stop. In these particular situations a very important role is played by the automation system that has to manage the whole propulsive chain (i.e. main engine, mechanical transmission and propeller) in a safe and efficient way. With regard to this, a simulation based design methodology is adopted to develop and test new control schemes for ship propulsion. The proposed control layout is applicable to any type of propulsion systems equipped with controllable pitch propellers, since it is mainly based on the automatic adjustment of the propeller pitch. Thus the desired performance requirements are met through adaptive control strategies able to address the complex issues of slam start, crash stop and similar stressful manoeuvres. The adaptivity of the automation process to several critical propulsive conditions reduces significantly the number of the control parameters to be estimated, as recently demonstrated by the automation design of a new twin-screw ship. For this application, the comparison between simulation results and sea trials data is finally shown for validation design purposes.

1. Introduction

Current marine propulsion systems are notable for their high performance and flexibility, difficult features to be achieved without the development of an efficient control system. The large power available to the propellers entails a careful management of the propulsion machinery, in every propulsive condition. Especially during critical manoeuvres (e.g. slam start, crash stop, tight turning circles, …), the automation designers have to develop proper control strategies and set a lot of parameters, normally based on their experience, in several ship propulsion modes. The identification of the proper solution among all the possible combinations is rather difficult and time consuming. In light of this, special control functions, characterized by an adaptive behaviour, could be very useful because they would reduce the number of variables to be assessed.

Time-domain simulation can be used to evaluate the effectiveness of these algorithms, especially for the representation of ship critical manoeuvres that could dangerously stress the whole propulsion system (Altosole et al., 2012). Many simulation studies on ship manoeuvrability can be found in the scientific literature but it is not easy to represent every manoeuvre by a single numerical model. An attempt to develop a comprehensive unified versatile mathematical model, suitable for the all types of manoeuvres in still water, has been recently undertaken by Sutulo and Guedes Soares (2015): in their study, the comparisons with full-scale data (available for the full helm turning tests, crash stop tests and bow thruster turning of a shuttle LNG carrier) show reliable simulation results, practically without special tuning of the model.

On the contrary to what happens for manoeuvrability issues, the machinery behaviour during demanding manoeuvres is rather less investigated in the available literature. The most stressful conditions for the prime mover, propeller and mechanical transmission can be experienced during the ship emergency manoeuvring, as in the case of slam start and crash stop. As well known, the first one is traditionally referred to the vessel acceleration from zero speed to the full power condition, while the second one is the ship stopping, as quickly as possible, starting from the maximum speed of the vessel. Especially during crash stop, usually performed to avoid collisions, the main engine and propeller are subjected to severe stress and loading. From this point of view, relevant scientific papers exist on the propeller structural safety in this particular emergency situation. In the available literature, the prediction of loads on the propeller during crash stop is usually performed by using propeller series charts or, more specifically, CFD analyses, in order to evaluate the structural safety of the blades. In Hur et al. (2011), propeller torque values are estimated by Wageningen B series characteristics and compared with sea trial data, in spite of the difference of the propeller blade shape and flow steadiness between series and recordings. Wageningen results during crash stop provide slightly higher torque values but the discrepancies can be considered marginal in evaluation of the structural safety. However, series charts

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Nomenclature

A	yoke area
B	oil bulk modulus
C_{ip}	oil leakage coefficient
$\boldsymbol{C}$	Coriolis centripetal matrix
e	error
n	rotational speed
$\bar{n}$	rotational speed corresponding to the maximum lever position
n_c	commanded rotational speed
p_{oil}	oil pressure
t	time
K_D	derivative gain
K_I	integral gain
K_P	proportional gain
I_b	moment of inertia of the propeller blade
I_p	polar inertia
$\boldsymbol{M}$	ship inertia matrix
q_i	oil volumetric flow
Q_E	engine torque
Q_{Elim}	engine torque limit
Q_f	shaft friction torque
Q_{hyd}	hydraulic torque
Q_P	propeller torque
Q_S	shaft torque
Q_{Slim}	shaft torque limit
$Q_{-\phi}$	torque due to the forces interaction between blade and bearing of the propeller
S_i	automation signal value
$\boldsymbol{v}$	ship speed vector
V_c	chamber volume
x_p	piston position
$\boldsymbol{\tau}_H$	forces and moments acting on ship hull
$\boldsymbol{\tau}_P$	forces and moments acting on ship hull
$\boldsymbol{\tau}_R$	forces and moments acting on ship rudder
φ	propeller pitch
φ_c	commanded propeller pitch
φ_r	propeller pitch reduction value
$\Delta\varphi$	propeller pitch tolerance
Δrpm	revolutions per minute tolerance

cannot predict the pressure distribution on the propeller blade; hence CFD simulation is suggested to represent the hydrodynamic load acting on the propeller. About this, Black and Swithenbank (2009) have examined the water flow velocities, measured during a crash-back test of a model propeller: experimental data, concerning mean and extreme loading conditions, have been used in a strip theory approach to develop loads for finite element analysis, in order to assess stresses on the individual blades.

Structural safety of the several propulsion components (propeller, shaft line, thrust-bearing and main engine) can be ensured also by adopting proper control strategies to avoid overloading during critical manoeuvres. From this point of view, numerical simulation can be used to evaluate the effectiveness of original control devices, as reported by Yabuki and Yoshimura (2010) and Wirz (2012). In the first mentioned work, a simulation study is described to evaluate the ship-handling method during the stopping manoeuvre: a turning moment is applied to the ship by the maximum rudder angle steering prior to the reversing operation of the Controllable Pitch Propeller (CPP). The simulation analysis confirms that CPP ships can be sufficiently controlled by the proposed method.

The combination of a slow-speed two-stroke diesel engine and a Fixed Pitch Propeller (FPP) is rather disadvantageous from the point of view of the crash stop performance. Consequently, Wirz (2012) proposes and simulates a novel method of applying a braking torque to the FPP by means of water injection into the engine cylinders during unfired operation.

As regards the characteristics and requirements of a good control propulsion system, able to prevent overloads and possible failures of the ship machinery, very little was written so far. Banning et al. (1997) introduce a tracking control system aimed at saving fuel and optimizing efficiency. A propulsion control procedure, based on several controllers switching between them to cover the whole operating range of the vessel, is proposed by Lopez et al. (2010).

However, except for occasional works, the control issue in marine literature is often addressed from the manoeuvring point of view, such as in the path-following problems (Skjetne et al., 2005; Fossen, 2011) and unmanned surface vehicles (Breivik et al., 2008) but a proper investigation of the engines and actuators behaviour is a key point for the correct evaluation of every ship manoeuvre (Martelli, 2015).

In line with the latter consideration, the present article deals with the development of some proper control algorithms for the ship handling during slam start and crash stop. A first theoretical application was considered during the control scheme design of an innovative propulsion system (Altosole et al., 2012) characterized by a very flexible use of the different engine types onboard (gas turbine and electric motor). Simulation results are shown and discussed, in order to justify the choice of the proposed special control functions. Similar simulation approaches to represent crash stop dynamics are adopted by Krüger and Haack (2004) and Schoop-Zipfel et al. (2012). In both works, the authors address the negative influence of the wind milling effect (i.e. propeller driven by the water) on the whole propulsion system during the ship stopping but do not provide any details concerning the control procedure to manage this critical situation.

The automation logics presented in this study are suitable for CPP propulsion systems, since they are characterized by an adaptive behaviour due to the automatic computation of the propeller pitch reference. By this way, it is possible to drive a wide range of possible heavy accelerations and stopping manoeuvres, as demonstrated by the full-scale validation shown at the end of the article.

2. Overall control system and design methodology

In this section, the main characteristics of a possible control system layout are described for a generic marine propulsion system. Prime movers can be diesel engines, gas turbines or even electric motors. The controller architecture is based on machinery regulation and protection functions. The purpose of the main propulsive regulation is to provide the proper revolutions signal to the engine, in order to keep the commanded propeller speed value achieving the desired velocity of the vessel. Protection logics aim at preserving propulsion machinery from overloads (i.e. over-torque, over-speed, over-temperature, etc…). All three types of engines above mentioned are usually controlled in terms of their rotational speed. In fact the overall controller calculates the signal reference to the engine governor over time, based on PID algorithms applied to revolutions error between commanded and actual values. This control signal is finally transformed by the governor into the required mechanical torque, by means of acting on the fuel flow in the cases of diesel engines and gas turbines, or on the frequency in the case of electric motors.

For the sake of clarity, the main control features are resumed through the control scheme of Fig. 1, referring to the single shaftline of a generic propulsion system equipped with Controllable Pitch Propellers (CPPs).