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Gain Scheduling Control of a Combined Diesel or Gas Ship Propulsion System with Parameter-Dependent Delay

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Abstract: This paper presents the main features of a combined diesel or gas ship propulsion system and a control strategy to be applied to its velocity channel. Operating limits, saturations and parameter-dependent delays make the system dynamic behavior highly nonlinear. The main objective is to control the ship velocity by using identification techniques and a combination of Smith predictor with a gain scheduling control method. The aim is to meet the specified time-domain performance with disturbance rejection over the entire operating range. Numerical results clearly show the advantages of using the proposed control technique.

Keywords: Ship speed control, Smith predictor, gain scheduling, PID, system identification, delayed systems.

1. INTRODUCTION

Modern warships are designed to operate in a wide range of velocities, involving large rotor speed and power variations. It is usually required a combination of propulsion engines, rotation speed and pitch propeller angle to meet different operating conditions as cruising or war maneuvers. Nowadays, the most used propulsion engines for war operations are gas turbines. High power-to-weight ratio, fast response and high reliability are the key features of gas turbines that justify their use for war maneuvers. On the other hand, small gas turbines and high speed diesel engines are suitable for cruising operating conditions (silent-mode operation) and have relatively low fuel consumption, while keeping enough power supply.

This paper focuses on a Combined Diesel or Gas (CODOG) ship propulsion system, which is comprised by a gas turbine and/or diesel engines and Controllable Pitch Propellers (CPP), as described in Section 2.1. The study is based on a mathematical modeling of an actual ship propulsion system. The system model was recently developed jointly by the Automation and Control Laboratory of the Polytechnic School/University of São Paulo (LAC/EPUSP) and the Brazilian Navy Research Institute (IPqM), LAC/EPUSP (2006). The dynamical model of the overall velocity control channel is highly nonlinear, involves parameter-dependent delays and was obtained through detailed modeling of each subsystem.

The objective of the control strategy presented here is to track a reference speed value considering disturbance rejection. The technique is easy to apply and combines simple linear identification, Smith predictor and gain scheduling methods to meet the specified time-domain performance over the entire operating range. Numerical results clearly show the advantages of using the proposed control technique.

Other techniques have also been used to achieve similar performances for a gas turbine propulsion plant, as an auto-adaptive control method, in Morishita and Brinati (1986), and a strategy for optimal multivariable minimum control effort regulation, in Whalley and Ebrahimi (2002).

This paper is organized as follows: Section 2 describes the ship propulsion system, its inner feedback control loops and the disturbances it can be submitted. Section 3 shows the benefits of considering an additional speed control loop for different control strategies and single or multiple operating points. The proposed gain scheduling control design is presented in Section 4 and its performance is compared with those controllers presented in the previous section. Section 5 presents the conclusions.

2. A CODOG SHIP PROPULSION SYSTEM

This section presents a brief description of the studied ship propulsion system.

2.1 Plant Description

As shown in Figure 1, the plant consists of a mechanical assembly connecting the port and starboard propeller shafts to three different engines: a gas turbine and two diesel engines.

A system of gears provides the necessary speed reduction between the machinery and propellers. A set of four self synchronous clutches allows the various engines to be coupled to the propeller shafts in several ways. Between gears and diesel engines or gas turbine there are fluid couplings that transmit more or less rotating mechanical

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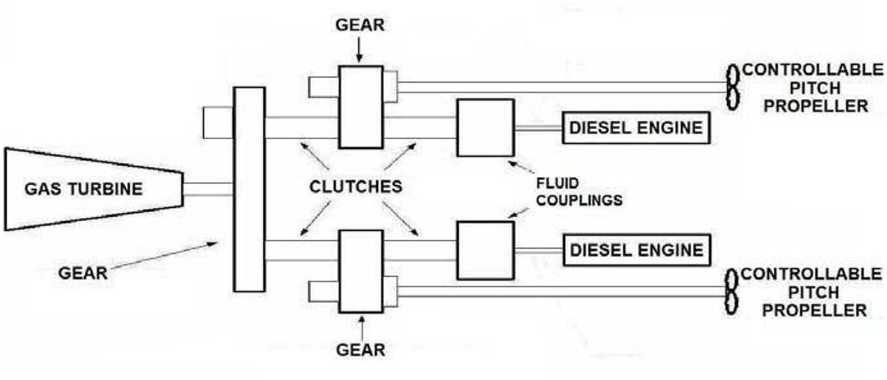

Fig. 1. Ship propulsion system

power to the propulsion plant, depending on how full they are. Controllable pitch propellers move the vessel forward or backward and are regulated by a local control system, which hydraulically drives the blades angle to track a reference pitch signal. The gas turbine also has a fuel controller, directly coupled to it, that regulates the flow of fuel and hence controls the rotating mechanical power.

2.2 Inner Feedback Control Loops

Figure 2 shows a simplified diagram of the inner propulsion control loops. Velocity control is performed in open loop, i.e., once a desired reference speed is selected, it is expected the actual ship velocity reaches this value in a given settling time. The control system involves the following subsystems: two identical engine control subsystems, a turbine control subsystem, and two identical propeller control subsystems. These subsystems operate in closed loop, since the engines and turbine rotation speed and the pitch angle of the propeller blades operate in a feedback control scheme.

The propulsion control system has three reference input signals: desired speed, operating mode and actuation mode. The desired speed is selected by moving a lever that vary the Power Control Level (PCL) from 0% to 100% of its maximum value (100% PCL is equivalent to the maximum velocity the ship can achieve when the two propellers are powered by the turbine, in nominal conditions), and is located on the bridge of the ship and on the machine control center. There are 11 possible actuation modes, according to the selected configuration and amount of propulsion equipments to be used (number and combination of turbine, engines and propellers) in a given maneuver. After choosing the actuation mode, the propellers pitch angle and the engines/turbine rotation range that allow the ship to reach a specified velocity (given in % PCL), one of the following three operating modes has to be selected to determine the propeller shaft rotation:

- ultra quiet mode: the propeller shaft rotation is minimized;
- normal mode: a minimum propeller shaft rotation is set, such that there is still no need to operate the CPP hydraulic pump and it should be possible a combination of engines with turbine;
- power mode: a higher propeller shaft rotation is set, such that there is a power reserve and the ship velocity control channel be more sensitive to changes in the reference signal % PCL.

2.3 System Disturbances

During its operation, the vessel may be subjected to some disturbances such as: deteriorations of the hull and propeller conditions (dirt and incrustation), ship loading conditions (heavier or lighter), machine power loss, wind, ocean currents etc. These disturbances impact the ship performance and may causes steady-state errors and/or slow transient velocity responses. Simulations were performed to compare the effects caused by such interferences and showed that the final speed can be reduced by up to 4 knots in relation to the reference value. Figure 3 shows the relation between the steady-state vessel speed and the propeller rotation, when the pitch angle is kept constant at 31 degrees, for the model with and without disturbances. Hull incrustation and an additional load mass of 20% were considered as disturbances. Steady-state errors can be compensated and transient responses can be shaped by implementing an outer speed control loop.

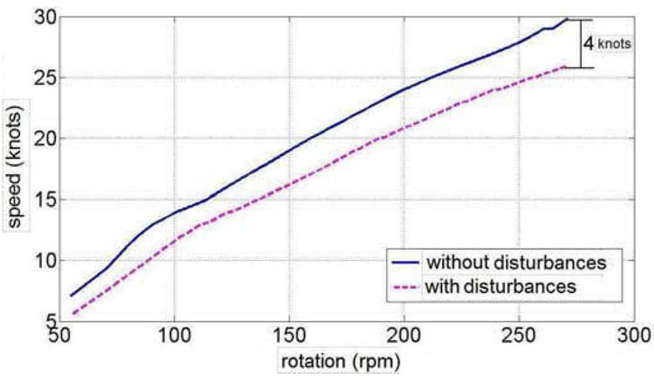

Fig. 3. Steady-state vessel speed depending on the propeller rotation for a pitch angle of 31 degrees (normal mode)

3. ADDITIONAL SPEED CONTROL LOOP

This section considers an additional speed control loop for different control strategies and single or multiple operating points. In the rest of the paper, we consider only the two diesel engines are supplying rotating mechanical power to the two propellers in the normal operating mode.