IDENTIFICATION AND COMPENSATOR DESIGN OF AN AERO-DERIVATIVE GAS TURBINE APPLIED TO SHIP PROPULSION

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Abstract. *This paper presents a speed compensator design applied to an aero-derivative gas turbine. The studied turbine is a component of a combined diesel or gas propulsion system of a warship, which also encompasses a couple of diesel engines and controllable pitch propellers. The focus is only on the solution of the turbine speed control problem, an inner control loop of the ship velocity control system. The aim is to meet the specified time-domain performance over the entire operating range by using a simple proportional-integral structure, since the available commercial off-the-shelf controller did not allow the implementation of more advanced control strategies. Saturations and constraints on the fuel feed rate and on the combustion process make this system highly nonlinear, and then hard to be controlled in practice. A black-box identification method based on input-output data from sea tests performed in a war vessel has been used to find a representative linear time invariant model for this system. This model was utilized for control design purposes and, despite the system nonlinearities, numerical simulations showed that the tuned controller meets the closed-loop requirements on a wide range of operating conditions.*

Keywords: *gas turbine control, ship propulsion system, PID, system identification*

1. INTRODUCTION

Modern warships are designed to operate in a wide range of velocities, involving large engine 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 deals with 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. Previous papers (Pinto *et al.*, 2008) and (Pinto and Pellanda, 2010) presented a controller design for the velocity channel of the ship propulsion control system. The objective of that control strategy was 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.

Here, the focus is only on the solution to the turbine speed control problem, an inner control loop of the ship velocity control system. According to (Mu *et al.*, 2002) and (Mu *et al.*, 2005), saturations and constraints on the fuel feed rate and on the combustion process make this system highly nonlinear, and then hard to be controlled in practice. Additional difficulties also appear for assuring an adequate performance over a wide system operating range. Besides, the turbine manufacturer did not provide any mathematical model for this system. Then, a black-box identification method based on input-output data from sea tests performed in a war vessel has been used to find a representative Linear Time Invariant (LTI) model for this system. This model was utilized for control design purposes.

A simple Proportional-Integral (PI) structure was used, since the available commercial off-the-shelf controller did not allow the implementation of more advanced control strategies. The controller design problem was successfully solved by using open-loop tuning methods, such as Ziegler-Nichols (Ziegler and Nichols, 1942), and Matlab's Optimization Toolbox. Numerical results clearly show the effectiveness of the proposed control technique.

Other techniques have also been used to achieve similar performances for a gas turbine, as an optimum PI controllers design in (Mu *et al.*, 2002); a Gain Scheduling Proportional-Integral-Derivative (PID) controller and a Nonlinear Model Predictive Vontrol (NMPC) in (Mu *et al.*, 2005); and a PID-like fuzzy controller with Field Programmable Gate Array (FPGA) in (Yao, 2010).

This paper is organized as follows: Section 2 describes the ship propulsion system, its inner feedback control loops and the gas turbine. The identification of an LTI model for this system is presented in Section 3. Section 4 shows the compensator design and closed-loop simulations. Section 5 concludes the paper.

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.

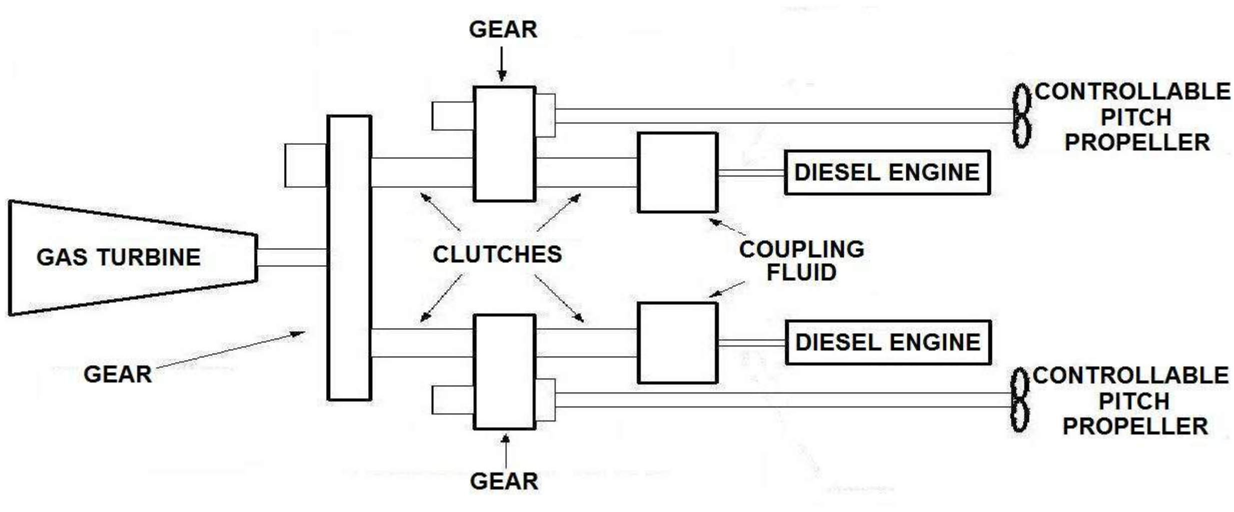

Figure 1. Ship propulsion system.

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 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 (the subject of our study), 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 a combination of engines with turbine be possible;
- 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.

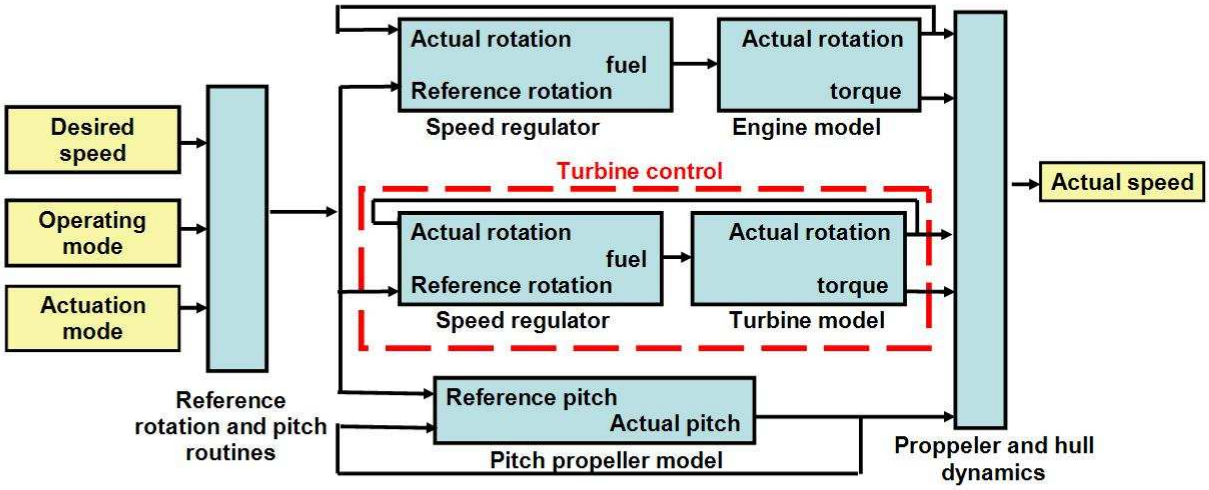

Figure 2. Simplified diagram of the inner propulsion control loops.

2.3 Gas Turbine

According to (Boyce, 2001), the gas turbine is a thermal machine whose operation can be described by the open Brayton cycle model. Despite the variations in relation to this (ideal) conventional thermodynamic cycle, it is still a good way to model the power plant. The gas turbine has three major components (Figure 3): a gas compressor, a combustion chamber and an expansion turbine, sometimes called High Pressure (HP) turbine, which composes the called gas generator. Except for flight applications, usually there is another turbine named power turbine or Low Pressure (LP) turbine, coupled only by the exhaust gases from HP turbine, which will drive the generator, compressor, shaft or other devices.

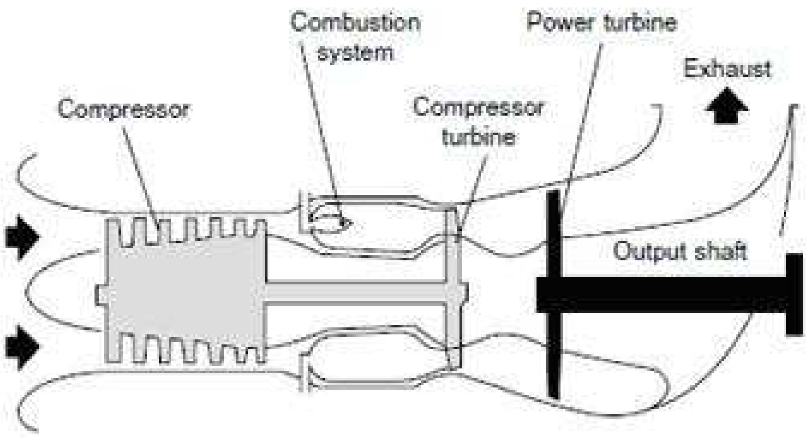

Figure 3. Example of a gas generator and power turbine configuration.

The studied engine is the LM2500 marine gas turbine, which is derived from GE Military TF39 and turbofan turbines applied as commercial flight motors. According to (Woodyard, 2009), the LM2500 marine gas turbine is a simple-cycle, two-shaft (one is used to drive the gas generator, compressor and HP turbine; the other is used to deviate some load to the LP turbine) engine, comprising a gas generator and a power turbine. This turbine is shown in Figure 4.

The turbine rotation regulation system uses a Woodward Atlas PC off-the-shelf controller which manipulates the fuel flow by Power Level Angle (PLA) actuator (GE, 2007). The red dashed line in Figure 2 shows the turbine control scheme.

3. LINEAR TIME INVARIANT MODEL

In order to design a speed controller, an identification procedure to obtain an LTI model that approximates the nonlinear system dynamic behavior must be performed because its mathematical model is not available. Therefore, the idea is to identify a linear model based on nonlinear input-output data collected from sea tests performed in a war vessel (GE, 2010). These data were collected from the actual system operating in a closed loop with the original PI_1 controller (K_{p_1} = 5,25

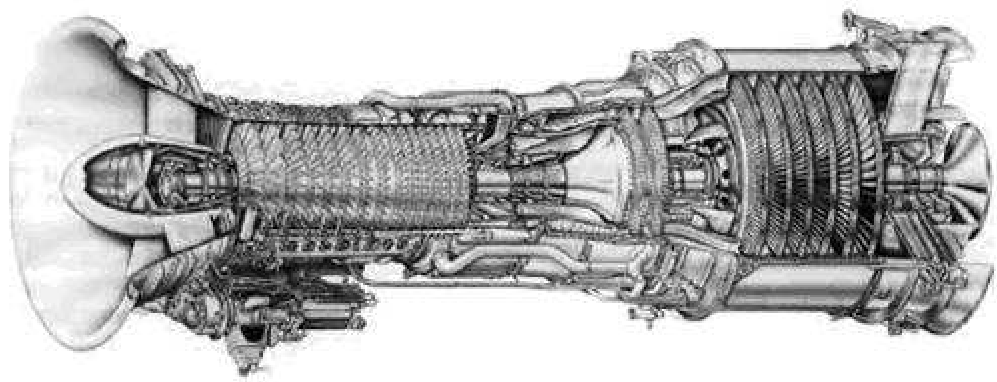

Figure 4. Cutaway of GE Marine Engines' LM2500 aero-derived gas turbine showing (from left to right) the compressor, annular combustor, HP turbine and LP power turbine.

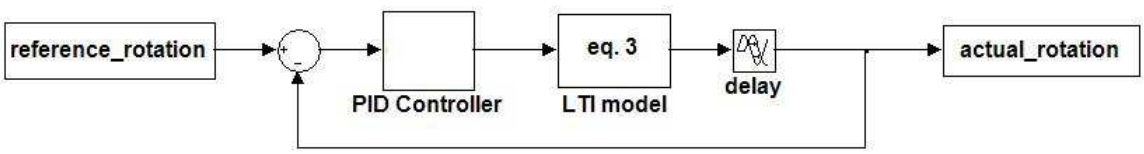

Figure 5. Block diagram of the turbine rotation control system.

and K_{i_1} = 0,01).

The block diagram of the turbine rotation control system is depicted in Figure 5. The PID block used to regulate the turbine rotation is a standard function from a specialized software used to program the controller.

The PID algorithm of PI_1 block implementation proposed by the manufacturer is different from the commonly used structure and has the following transfer function:

$$K(s) = \left(\frac{K_p K_i}{s}\right)\left(\frac{s}{K_i} + 1\right)(sK_d + 1) \tag{1}$$

For this turbine rotation control channel, we propose the use of a PI controller to accelerate the movement of the process towards the set point (the fuel flow control needs a fast response) and eliminate the residual steady-state error that occurs with a proportional only controller. Once a PI controller is adopted, we have $K_d = 0$ and the Equation (1) is reduced to:

$$K(s) = K_p + \left(\frac{K_p K_i}{s}\right) \tag{2}$$

where K_p is the proportional gain and K_i is the reset time in repetitions per second.

The input signal (turbine rotation reference) used for the identification is a rich sequence of steps whose amplitudes have been chosen such that the final speed value covers most of the scheduling range, thus inducing significant variations in the dynamic coefficients. The MATLAB's System Identification Toolbox has been used to find this LTI model. Despite the system complexity, a single delayed LTI model is able to properly represent the nonlinear system behavior:

$$G(s) = \frac{123,9}{s^2 + 5816,0s + 133,8} e^{-0,0189s} \tag{3}$$

Figure 6 compares the nonlinear and linear model (3) closed-loop responses to a given sequence of step inputs. Model (3) was utilized for control design purposes.

4. COMPENSATOR DESIGNS

This section shows two compensator designs and numerical results. According to (Marinha do Brasil, 2005), the following performance specifications were established for the closed-loop system:

- overshoot ≤ 12 %;

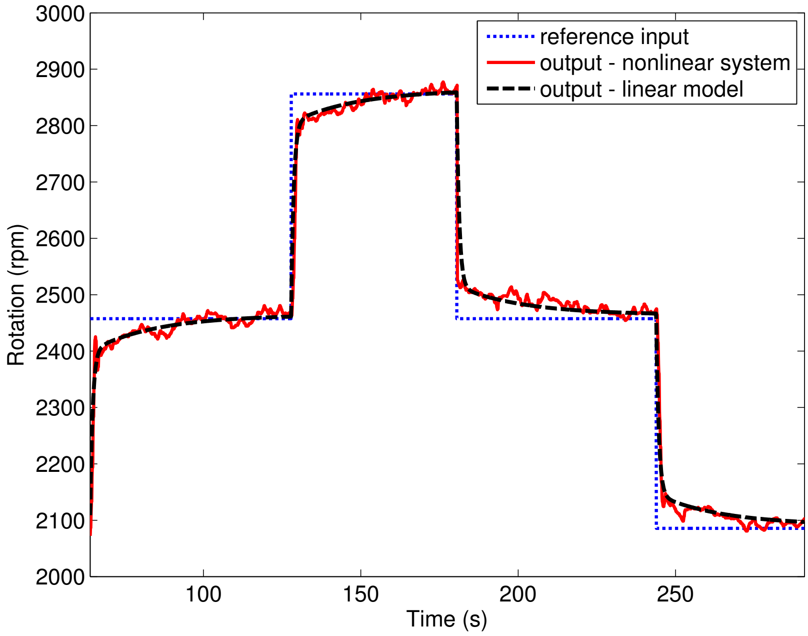

Figure 6. Linear model and nonlinear system closed-loop responses.

- undershoot $\leq$ 8 %;
- settling time $\leq$ 30s for a 2%-steady-state error;
- rise time as short as possible.

4.1 Ziegler-Nichols Tuning

Open-loop tuning methods are perhaps the most widely used techniques for tuning PID controllers (Visioli, 2006). According to (Johnson and Moradi, 2005), these techniques, which include the Ziegler-Nichols method, for instance, are generally used to solve servo control problems.

The computation of PI_2 parameters was performed by applying the Ziegler-Nichols step response tuning rules to the linear model (3). Computed proportional and integral gains are K_{p2} = 9,6835, K_{i2} = 1,2576, respectively.

Figure 7 compares the performance of the closed-loop linear system controlled by PI_1 (original controller) and PI_2. The latter presents a faster response, but the maximum overshoot was excessive compared to the specified performance. This result is not surprising once Ziegler-Nichols tuning rules are meant to give PID loops better disturbance rejection performance, instead to minimize or eliminate overshoot.

4.2 Optimum PI Controller

The controller designed by using the Ziegler-Nichols tuning rules, PI_2, needs a fine tuning in order to meet the performance specifications. The control strategy proposed in this section uses the Simulink Design Optimization from the MATLAB‘s Optimization Toolbox to compute an optimum PI controller PI_3.

The algorithm looks for a good balance between performance and robustness.

The algorithm designs the controller by choosing a bandwidth to achieve that balance, based upon the open-loop frequency response of the linearized model. When the time response, bandwidth or phase margin changes, the algorithm computes new PI gains.

The parameter of PI_2 was used as an initial guess for the optimization process. The computed PI_3 gains are K_{p3} = 4,0470, K_{i3} = 0,1324.

Figure 8 compares the performance of the closed-loop linear system controlled by PI_1 (original controller) and PI_3. The optimum PI controller presents a faster response, while keeping the overshoot within the specified limit.

5. CONCLUSION

This paper presented the main features of an aero-derivative gas turbine applied to a warship that uses a CODOG propulsion system and a simple control strategy based on an optimum PID Controller to be applied to its rotation control channel. Numerical results showed that the proposed control strategy met the specified time-domain performance over a

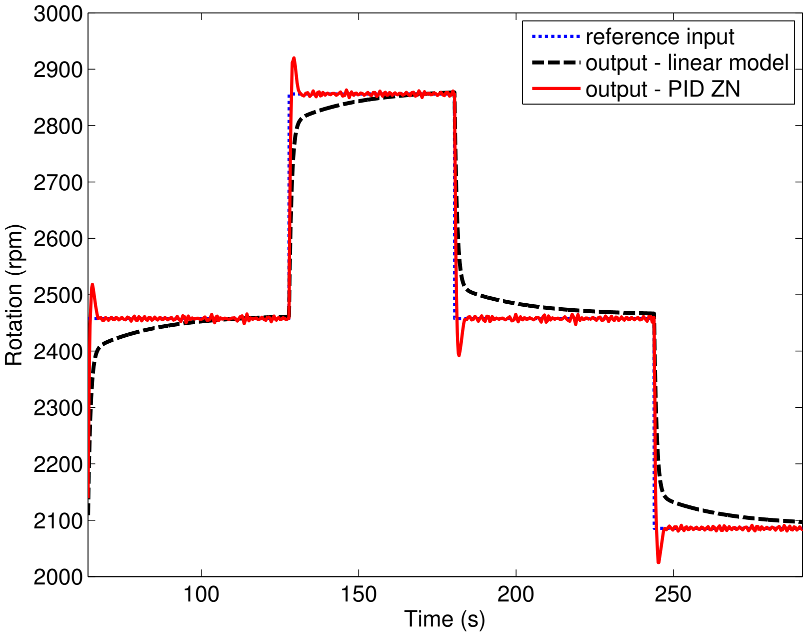

Figure 7. Closed-loop system with PI_2 controller (Ziegler-Nichols) performance.

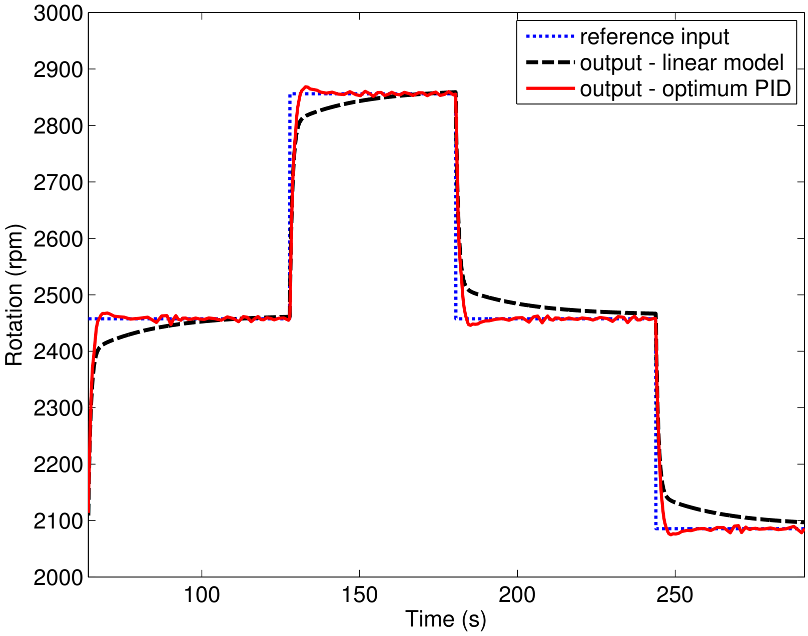

Figure 8. Closed-loop system with PI_3 controller (optimum) performance.

wide operating range and the PI controller was adequate for the gas turbine system. The next step is to implement it in the actual system.

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