ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Adaptive fault-tolerant PI tracking control for ship propulsion system

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ARTICLE INFO

Keywords:
Fault-tolerant control
Adaptive PI controller
Tracking control
Ship propulsion system

ABSTRACT

This paper studies the fault-tolerant tracking control issues for the ship propulsion system. The propulsion system with one engine and one propeller is first introduced, and the faulty model with loss of actuator effectiveness is formulated. By utilizing the H_∞ output feedback technique, the nominal proportional-integral (PI) controller is designed with its gains analytically determined, yet ensuring the desired tracking performance in the fault-free case. Furthermore, to accommodate loss of actuator effectiveness faults, a fault-tolerant PI control scheme is proposed, including the adaptive tuning law to adjust controller gains online. The proposed strategy is not only simple and easy to implement, but also guarantees the graceful tracking performance and fault-tolerant capability. Finally, a case study on the ship propulsion system is presented to demonstrate the effectiveness of the proposed methods.

1. Introduction

The ship propulsion system is a safety-critical equipment in the complex marine systems. Faults in the components of the propulsion system could result in the loss of maneuverability and severe damage. Therefore, it is of paramount importance to enhance the reliability and fault-tolerant capability of the ship propulsion system, not only on the level of individual components, but also on the overall system. The studies of fault-tolerant control have received much attention in the past few decades [1–7]. Employing the well-developed control theories, many methods have been proposed to cope with the fault-tolerant controller design problem, such as: robust fault-tolerant control [1], adaptive fault-tolerant control [8–10], and integrated fault diagnosis and fault-tolerant control with the observer-based realization of Youla-parameterized controller [11–13]. Meanwhile, the applications of fault-tolerant control methods to the benchmark of the ship propulsion system have been presented in Refs. [14–18].

The stable tracking of the ship speed is a significant objective for the ship propulsion system. And the theoretical investigations of the tracking control have been extensively explored in the control field. Many schemes are to track the output of a given reference model with the guaranteed linear quadratic regulation or H_∞ performance [19,20]. These methods require a prior knowledge of the reference model. However, in the tracking control of the ship speed, there is often no reference model of the ship speed. There exist two different strategies to deal with this issue. One is designing a tracking control scheme with the extended state feedback [21], the other is applying the multivariable PI controller by solving a static output feedback control problem [22,23]. Traditionally, the PI controller is widely adopted to the tracking control for the ship propulsion system, due to its simplicity, functionality and effectiveness [17,18].

Proceeding from the above observation, the ship propulsion system is required to satisfy the specific fault-tolerant capability and tacking performance. To this end, the fault-tolerant tracking control approaches for the ship propulsion system have been studied in Refs. [16–18]. The existing results mainly focus on designing reconfiguration strategies based on the fault diagnosis unit. However, there are two major drawbacks for these schemes. First, the determination of nominal PI controller gains is a time-consuming “trial and error” process. Second, the fault diagnosis unit is required for the controller reconfiguration. Until now, few works have fully investigated the fault-tolerant tracking control for the ship propulsion system with the PI gains analytically determined yet without fault diagnosis process.

Recently, by combining adaptive techniques and some classical control methods such as neural network control and flight control, the strategies of adaptive neural network control [9] and adaptive flight

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https://doi.org/10.1016/j.isatra.2018.07.004
Received 29 May 2017; Received in revised form 23 May 2018; Accepted 6 July 2018
0019-0578/

Please cite this article as: Zhao, Z., ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.07.004

control [10] are proposed with fault tolerant capability. Meanwhile, some researchers have attempted to design the PI controller with adaptive mechanism [24–26]. To the best of authors' knowledge, the existing studies on the adaptive PI control have been either focused on the systems with disturbances [24] or actuator faults [25,26]. This paper studies the fault-tolerant tracking control for the ship propulsion system with disturbances and loss of actuator effectiveness faults. The main contributions of this paper can be summarized as follows:

1. The nominal PI controller is designed with the PI gains analytically determined to ensure the stable tracking for the ship propulsion system with disturbances.
2. An adaptive law is designed to adjust the PI gains to actuator faults. The proposed adaptive PI control scheme exhibits the graceful fault-tolerant capability without the fault diagnosis unit.
3. The proposed adaptive fault-tolerant PI control scheme is verified on the benchmark of the ship propulsion system.

The paper is organized as follows. Section 2 first introduces the ship propulsion system and Section 3 gives the problem formulation. In Section 4, the nominal PI tracking control scheme for the ship propulsion system with disturbances is proposed. Section 5 presents an adaptive fault-tolerant PI tracking control strategy to tolerate actuator faults. In Section 6, simulation results on the ship propulsion system model are illustrated. The conclusions are given in Section 7.

Notation: In the following, standard notations will be adopted. $\mathscr{R}^n$ denotes the n-dimensional Euclidean space, $\mathscr{R}^{n\times m}$ the set of all $n \times m$ real matrices. The superscript "T" represents the transpose of a matrix, $He(X) = X + X^T$, and "$*$" denotes the symmetric part of a matrix. $\|\cdot\|_\infty$ stands for the H_∞ norm of a transfer function matrix.

2. Ship propulsion system

The control objective of the ship propulsion system is to make the ship speed V track a given ship speed command ω. The tracking control structure for the ship propulsion system is illustrated in Fig. 1, including, an adaptive PI controller, the actuator dynamics, and the ship propulsion system model. The nonlinear and linear models of the ship propulsion system with one engine and one propeller are presented. The design of adaptive PI controller is presented in the following sections.

2.1. Nonlinear model

In this part, referring to the literature [16,18], the shaft speed dynamics, the ship speed dynamics, and the actuator dynamics are presented.

2.1.1. Shaft speed dynamics

Consider the shaft speed dynamics given by

$$I_m \dot{n} = Q_e - Q_p - Q_f \tag{1}$$

where I_m, n denote the inertial moment and the shaft speed. Q_e is the diesel engine torque, Q_f is the friction torque, and Q_p is the propeller torque with the following form:

$$Q_p = Q_1(\theta)n^2 + Q_2(\theta)nV_a \tag{2}$$

where $Q_1(\theta)$, $Q_2(\theta)$ are functions of the pitch angle θ. V_a is the velocity of the water that flow through the propeller disc (also called the advance speed) described as

$$V_a = (1-\kappa)V \tag{3}$$

where V is the ship speed and $\kappa \in [0.1, 0.4]$ is the wake fraction number.

The interpolating model of the propeller torque is given by

$$Q_p = \rho D^5 K_Q n^2,\quad K_Q = \alpha_1\theta + \alpha_2 J \tag{4}$$

where ρ is the water density, D is the propeller diameter, and K_Q is the torque coefficient. α_1, α_2 are constants depending on ship types, and J is the advance number given by

$$J = \frac{2\pi V_a}{nD}. \tag{5}$$

Remark 1. *This paper considers the situation that the shaft speed and the pitch angle are positive. When the shaft speed or the pitch angle is negative, similar results can be derived, which is out of the scope of this paper.*

2.1.2. Ship speed dynamics

Consider the ship speed dynamics described as

$$m\dot{V} = (1-\mu)T_p - T_h - T_w \tag{6}$$

where m denotes the ship mass, and μ is the loss coefficient of thrust due to disturbance of the pressure balance, which has a typical value between 0.05 and 0.2. T_h, T_w describe the hull resistance, and the external force due to wind and waves. T_p is the propeller thrust with the following form

$$T_p = T_1(\theta)n^2 + T_2(\theta)nV_a \tag{7}$$

where coefficients $T_1(\theta)$, $T_2(\theta)$ are functions of the pitch angle θ. Similarly, the interpolating model of the propeller thrust holds

$$T_p = \rho D^4 K_T n^2,\quad K_T = \beta_1\theta + \beta_2 J \tag{8}$$

where K_T is the propeller thrust coefficient, β_1, β_2 are the constants depending on ship types.

2.1.3. Actuator dynamics

The diesel engine is modeled as a first-order system [18] given by

$$Q_e(s) = \frac{K_e}{1 + T_e s}Y(s)$$

where $Y(s)$, $Q_e(s)$ are the Laplace transformations of the fuel index and the engine torque. K_e, T_e stand for the engine gain constant and time constant.

Similarly, The transfer function model of the pitch angle actuator is formulated as

$$\theta(s) = \frac{K_\theta}{1 + T_\theta s}u_\theta(s)$$

where $u_\theta(s)$, $\theta(s)$ are the Laplace transformations of the pitch angle

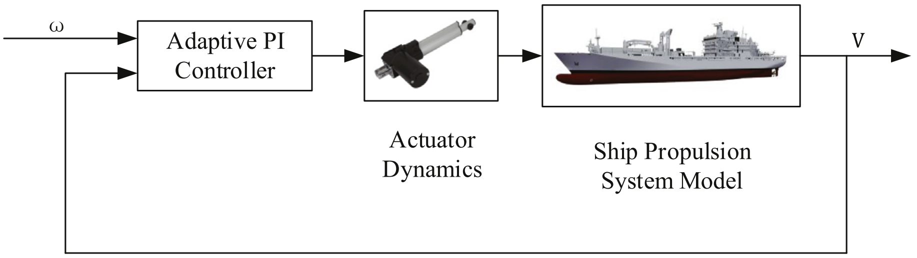

Fig. 1. Tracking control for the ship propulsion system.