Ocean Engineering 85 (2014) 21–31

Contents lists available at ScienceDirect

Ocean Engineering

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

Autonomous takeoff control system design for unmanned seaplanes

Huan Du, Guoliang Fan*, Jianqiang Yi

Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 27 July 2013
Accepted 5 April 2014
Available online 9 May 2014

Keywords:
Unmanned seaplane
Autonomous takeoff
Fuzzy identification
GPC
Wave forecasting

ABSTRACT

Unmanned seaplanes are special kinds of fixed-wing airplanes which can achieve autonomous takeoff and landing on water. Due to complicated hydrodynamic forces and unpredictable sea states, researches on modeling, dynamic analysis and controller design are still facing great challenges. In this paper, the dynamic characteristics and motion stability of the unmanned seaplane are firstly analyzed based on a nonlinear mathematical model. The proposed autonomous takeoff control system consists of two main parts: T-S fuzzy identification and generalized predictive control (GPC). A linear CARIMA model obtained through T-S fuzzy identification is used to represent the dynamic characteristics in different motion stages. Wave forecasting is considered in the GPC algorithm to improve the anti-waves capability and avoid unstable phenomena in high sea states. Simulations are performed in three different wave conditions, including calm water, regular wave and irregular wave. Moreover, GPC controller is compared with other disturbance rejection control solutions. The simulation results show that the proposed controller has good performances for autonomous takeoff of the unmanned seaplane.

1. Introduction

Seaplanes have played an important role in the world development of aircraft and they have seen extensive commercial and military applications in early years of modern aviation. After the World War II, the growing performance of land-based aircrafts led to a rapid market decline of the seaplanes and they faded into near obscurity (Silberg and Haas, 2011). However, in the last decade, with the development of unmanned aerial systems, unmanned seaplanes have appeared as a new type of vehicle, such as Sea Scout,[1] Gull[2] and Flying Fish (Eubank, 2012). As unmanned seaplanes can achieve autonomous takeoff and landing on water without inherent direction constraints of a narrow runway, they are widely applied in a broad range of circumstances, including surveillance and inspection, seaborne medical assistance, environment monitoring and so on.

However, there exist some inevitable problems, especially during the takeoff of unmanned seaplanes. Firstly, longitudinal dynamic instability phenomenon easily occurs when unmanned seaplanes slide along water surface at high speed, such as porpoising, characterized by an unstable coupling between heave and pitch degrees of freedom (Xi and Sun, 2006). This kind of motion may damage airborne equipment and fuselage structure, causing overthrow of the seaplanes. Secondly, it is still an intractable problem to deal with hydrodynamic interactions with water surface and unpredictable random waves in high sea states (Matveev, 2012). Due to the fact that unmanned seaplanes are always running at higher speed than common watercrafts, they are more inclined to be influenced by rough sea waves, resulting in some peculiar violent motions like jumping from wave crest and falling down to wave surface. These problems may make the unmanned seaplanes unable to operate in severe weather conditions and hinder the development and applications of unmanned seaplanes.

For manned seaplanes, pilots can adjust the attitude and speed to avoid occurrence of instability phenomenon according to human operational experiences. Furthermore, early works are mainly focused on the changes of design parameters to achieve stability, such as moving the center of gravity forward, introducing higher aspect ratios and larger radiuses of gyration (Payne, 1974). However, in high sea states, unmanned seaplanes encounter large sea wave influences and complex hydrodynamic impacts so that it is extremely difficult to implement autonomous takeoff or landing with stability guaranteed only through adjustment of geometric parameters. The effective way is to design high-performance controllers to improve the unmanned seaplanes sea-keeping ability, which refers to safety margins in common wave conditions and survivability in extreme waves.

So far as we know, there is no systematic and comprehensive public literature on controller designing methods for unmanned

* Corresponding author. Tel.: +86 13522082631.
E-mail addresses: huan.du@ia.ac.cn (H. Du), guoliang.fan@ia.ac.cn (G. Fan), jianqiang.yi@ia.ac.cn (J. Yi).

[1] http://www.oregoniron.com/industry-divisions/marine-industry/. Sea Scout UAV Information, Oregon Iron Works, retrieved 22.07.13.

[2] http://www.warrioraero.com/GULL/. Gull UAV Information, Warrior Ltd, retrieved 22.07.13.

http://dx.doi.org/10.1016/j.oceaneng.2014.04.003
0029-8018/

seaplanes except limited studies. The Flying Fish adopted traditional decoupled proportional-derivative control laws with a mode-based gain scheduling scheme without considering the effects of sea waves (Eubank et al., 2009). Recently, a longitudinal mathematical model has been developed for unmanned seaplanes (Zhu et al., 2012b). But with the model characterized by high nonlinearities, strong coupling and fast time varying, it is still a challenging problem to design efficient controllers compatible with a wide range of sea conditions. As concluded, controllers on unmanned seaplanes should be able to: (1) enhance vertical-plane stability to avoid porpoising; (2) predict the influences from random waves and reduce the water impacts; (3) keep the unmanned seaplanes safe and improve the sea-keeping ability in severe sea states.

Since the generalized predictive control (GPC) was proposed by (Clarke et al., 1987a, b), it has been one of the most popular and powerful model-based control methods for a wide class of nonlinear systems. The GPC algorithm generates a sequence of control signals at each sample interval via minimizing a quadratic cost function consisting of a weighted sum of errors and future predicted control increments. Compared with other model-based algorithms, GPC shows the following advantages: (1) it optimizes the control effort and exhibits robustness with respect to modeling errors and unmodeled dynamics; (2) it is capable of stabilizing systems with nonminimum phase, with variable or unknown dead-time, and with unknown order; (3) many practical parameters can be adjusted to improve control performance and this method can be actualized easily by numerical computer. Therefore, GPC not only receives widespread recognition in academia (Qin et al., 1996; Shook et al., 1992; Zhang et al., 2010), but also gains a broad range of applications in industrial process (Bordons and Camacho, 1998; Chang and Tsai, 2011; Geng and Geary, 1998; Lu and Tsai, 2007; Wu et al., 2012), flight control fields (Haley and Soloway, 2001; Hess and Jung, 1989; Lew and Juang, 2012, 2013), ocean engineering (Geng and Zhao, 2011; Phairoh and Huang, 2007) and so on. GPC controller has shown its advantages especially in anti-waves capability of ocean vehicles. For example, the adaptive GPC algorithm improved the performance of ship autopilot in Seastate 5 (Geng and Zhao, 2011). Phairoh and Huang (2007) studied ship roll mitigation by using a U-tube water tank with four dynamic controllers (PD controller, LQR controller, GPC and DPC). Numerical simulations showed that GPC achieved the best performance and could be easily implemented.

Generally, there are two fundamental steps in GPC implementation: (1) identification of the system; (2) use of the identified model to design a controller. In this paper, a controller based on T-S fuzzy identification and GPC algorithm is presented so as to improve the sea-keeping ability and achieve autonomous takeoff for the unmanned seaplane. T-S fuzzy identification has been proven to be suitable to model a large class of complex nonlinear systems since it can accurately approximate systems by using measured data along with a prior knowledge (Roubos et al., 1999; Su et al., 2007; Takagi and Sugeno, 1985). In order to utilize the real time information of waves and predict the wave influences in a certain time period, GPC algorithm with wave forecasting is proposed to enhance the unmanned seaplane anti-waves capability. This method is demonstrated to have satisfactory control performance by simulation in different sea conditions.

The remainder of the paper is organized as follows: Section 2 presents the nonlinear mathematical model of the unmanned seaplane and gives the calculation method of hydrodynamic forces. The dynamic characteristics and motion stability of the unmanned seaplane are analyzed in Section 3. In Section 4, a controller based on T-S fuzzy identification and GPC is designed to achieve autonomous takeoff for the unmanned seaplane. Furthermore, wave forecasting is added to the GPC algorithm to improve the anti-waves capability. Section 5 shows the performances of the controller in three different wave conditions. Finally, the concluding remarks are summarized in Section 6.

2. Nonlinear model of the unmanned seaplane

Combining fundamental physical laws and empirical methods, the longitudinal mathematical model is derived by Zhu et al. (2012b) for the unmanned seaplane. This model is used for system analysis and controller design using model-based methodologies in this paper.

2.1. Assumption

In order to proceed our research work, a few assumptions are made throughout this paper.

(1) The unmanned seaplane is a rigid body, and its mass is invariable during its takeoff.
(2) The influence of the earth's curvature is neglected and the coordinate system referenced to the earth is considered as an inertial system.
(3) There is no lateral disturbance during takeoff and only longitudinal motions are considered.

2.2. Coordinates definition and longitudinal mathematical model

Three right-handed coordinate systems are defined in Fig. 1 for the unmanned seaplane: Earth-fixed coordinate system with X_e, Y_e, Z_e axes, Body-fixed coordinate system with X_b, Y_b, Z_b axes and Steady-translating coordinate system with X_s, Y_s, Z_s axes. These coordinate systems are used to formulate the longitudinal dynamic equations for the unmanned seaplane. In Fig. 1, the variables that represent the angle of attack α, the angle of pitch θ and the velocity V are also indicated.

The forces acting on the unmanned seaplane can be categorized into weight, hydrodynamic forces, aerodynamic forces and engine thrust as shown in Fig. 2. The nonlinear longitudinal dynamic model of the unmanned seaplane is represented by Eq. (1).

$$\left.\begin{aligned} & m\dot{V} = T\cos(\alpha+\alpha_t) - D_a - N_w \sin\alpha - D_f \cos\alpha + G_{xa} \\ & mV\dot{\alpha} = mVq - T\sin(\alpha+\alpha_t) - L_a - N_w\cos\alpha + D_f\sin\alpha + G_{za} \\ & I_y\dot{q} = M_a + M_w + M_T \\ & \dot{\theta} = q \\ & \dot{x}_g = u\cos\theta + w\sin\theta \\ & \dot{z}_g = -u\sin\theta + w\cos\theta \end{aligned}\right\} \quad (1)$$

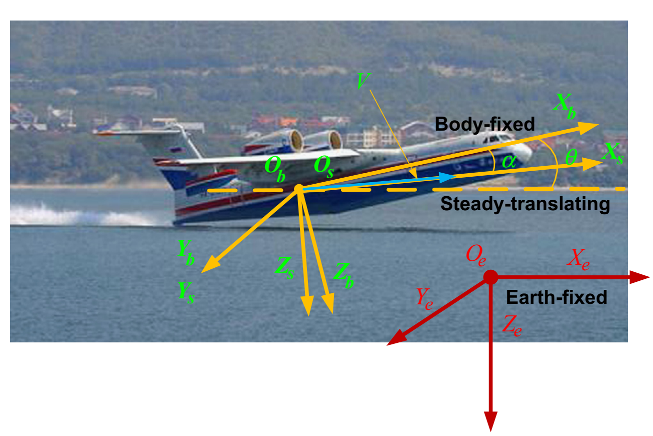

Fig. 1. Coordinate systems of the unmanned seaplane [1].