Aerospace Science and Technology ••• (••••) •••–•••

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Aerospace Science and Technology

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Automatic Carrier Landing System multilayer parameter design based on Cauchy Mutation Pigeon-Inspired Optimization

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A R T I C L E I N F O

Article history:
Received 6 January 2018
Received in revised form 29 April 2018
Accepted 11 June 2018
Available online xxxx

Keywords:
Automatic Carrier Landing System (ACLS)
Cauchy Mutation Pigeon-Inspired Optimization (CMPIO)
Multilayer design
Parameter optimization

A B S T R A C T

The parameter adjusting in Automatic Carrier Landing System (ACLS) is a time-consuming and tedious task. In order to improve the efficiency of the adjusting task and overcome the difficulties in the manual parameter adjustment, a multilayer optimization strategy, in which ACLS is clearly divided into four layers including inner loop, autopilot, guidance control and guidance compensation, is proposed in this study and adopted for the parameter design. Besides, a novel algorithm, named Cauchy Mutation Pigeon-Inspired Optimization (CMPIO) which is inspired by Cauchy distribution, is proposed to optimize ACLS parameters in each layer. Comparative simulations are conducted to verify the feasibility of the multilayer design strategy and the superiority of CMPIO. To enhance the authenticity of the simulations in the guidance compensation layer, some stochastic conditions are considered with different deck motion, air wake and radar noise turbulences alleviated by several rejection methods. The simulation results prove that the designed ACLS based on the multilayer design strategy satisfies the acknowledged criteria including the time and the frequency domain. Furthermore, the stability of the inner loop and the autopilot integrated with Approach Power Compensation System (APCS) are confirmed.

1. Introduction

Landing on carrier deck is a demanding task for carrier-based aircraft in all weather conditions. To help relieve the pilot and coordinate the attitude and the speed of aircraft, Automatic Carrier Landing System (ACLS) has been developed. ACLS incorporates shipboard tracking radar and digital computer to measure aircraft position and generate command via a radio data link [1]. The Automatic Throttle Control (ATC) in ACLS maintains on-speed angle of attack during an approach by modulating engine thrust [2] to complete precise landing assignment. In general, ACLS consists of flight control system, ACT, inertial navigation sensors, data link and the shipboard radar [3]. The main turbulences consist of deck motion, air wake and radar noise caused by shipboard radar.

In flight control system, to improve the capacity of resisting disturbances, H-dot ACLS is utilized and its superiority is confirmed by several flight tests [4]. Besides, modern control methods are also used for controller design, an Active Disturbance Rejection Control (ADRC) scheme is proposed in final approach [5]. Then the ADRC is confirmed it has better tracking performance and robustness in the presence of air wake and deck motion. Besides, an adaptive disturbance rejection method [6] is also proposed for the final approach control, and an adaptive sliding mode control law is proposed in [7] to help aircraft track desired landing trajectory. In guidance control, Proportional-Integral-Derivative (PID) controller is designed for the guidance loop and compared with the Proportional-Integral-Derivative-Double Derivative (PIDDD) controller and the Fuzzy-PID Controller [8]. Moreover, model predictive control method has also been used in the guidance law design [9], and the Back Propagation Neural Network has been used to predict the carrier landing position [10].

Nevertheless, in numerous ACLS former design researches, complicated system hasn't been clearly divided into several layers specifically and guidance parameters haven't been optimized [3,11], so that the former research can't take advantage of the structural feature of the ACLS.

The design goal of ACLS is to achieve a precise landing in both severe and normal conditions, which calls for a very high demand towards the parameters in ACLS [11]. Manual parameter adjusting task is a difficult and time-consuming task and it can't have excellent performance and take full use of the available advantages of ACLS, which exist in coupled control structure. To overcome the difficulties in manual adjusting, designing parameters

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https://doi.org/10.1016/j.ast.2018.06.013
1270-9638/

by intelligent optimization algorithm garners much attention in recent years [12]. Many intelligent algorithms and their improvement methods were put forward, such as Particle Swarm Optimization (PSO) [13,14], Ant Colony Optimization (ACO) [15], Differential Evolution (DE) [16] algorithm and so on. These methods have been extensively applied, including parameter identification [17,18], gliding trajectories control [19] and controller optimization [5,20].

Inspired by the pigeon homing behavior influenced by magnets [21,22] and sunlight [23], Pigeon-Inspired Optimization (PIO) [24] is firstly demonstrated by Duan in 2014. PIO contains two operators which named map and compass operator and landmark operator. Map and compass operator relies on magnetic field and sun, and the other operator relies on the landmark.

Cauchy mutation mechanism has been applied in several algorithms' improvements in recent years, especially in PSO and Gravitational Search Algorithm (GSA). The advantages of Cauchy mutation, including providing longer jumps as well as large perturbation [25] and having stronger global exploration capability [26], are verified with massive comparative experiments. Refer to [25] and [27], although PSO is improved with the particles' position changes multiplied with the additional coefficient which is related to the Cauchy mutation, improved algorithms are sensitive to the single scale parameter of the Cauchy distribution function. In [26] and [28], Cauchy mutation and an adaptive mass weighting strategy are adopted similarly in GSA's improvements. Nevertheless, these Cauchy mutation improvement strategies are complicated so that the performances of improved algorithms are determined by more setting parameters.

To further improve the algorithm's searching ability in complicated and multidimensional search space, inspired by the rational randomness of Cauchy distribution, improved PIO which named Cauchy Mutation Pigeon-Inspired Optimization (CMPIO) is proposed in this study. The Cauchy mutation mechanism in CMPIO is derived by Cauchy distribution and it is only determined by a fixed Cauchy distribution parameter. The innovation of this paper is to propose the CMPIO which has stronger searching ability, then it is utilized to design the parameters in four layers' ACLS. In this paper, at first ACLS is divided into four layers, including inner loop, autopilot, guidance control and guidance compensation. In the optimization of the four layers' ACLS which has numerous parameters, comparative simulations are conducted to verify the feasibility of the multilayer design strategy and the superiority of CMPIO. To enhance the authenticity of the simulations in the guidance compensation layer, some stochastic conditions are considered with different deck motion, air wake and radar noise turbulences alleviated by several rejection methods. With optimized parameters, then touchdown errors are tested in different turbulence conditions. Finally, the simulation results are used to prove that the designed ACLS based on the multilayer design strategy satisfies the acknowledged criteria including the time and the frequency domain. Furthermore, neglecting the nonlinear segments exist in APCS, the stability of the inner loop and the autopilot integrated with Approach Power Compensation System (APCS) are confirmed with the zero-pole distributive chart.

The remainder of this paper is organized as follows. In section 2, the F/A-18A aircraft longitudinal model and the components of ACLS are introduced specifically. A novel algorithm named CMPIO is proposed in section 3. Then the ACLS multilayer parameter design problem is demonstrated in section 4. Finally, comparative experiments are conducted in section 5 to verify the superiority of the designed ACLS and CMPIO.

2. Automatic Carrier Landing System

2.1. Longitude dynamic model of carrier-based aircraft

Supposing the earth curvature is neglected and the ground coordinate system is identical to the inertial coordinate system, the longitudinal linear small perturbation model of F/A-18A refer to [29] is utilized in this paper:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

where $x = (\Delta v/V_0, \Delta\alpha, \Delta\theta, \Delta q, \Delta h/V_0)^T$, $u = (\delta_e, \delta_{LEF}, \delta_{PL}, u_{wind})^T$ and $y = (\Delta h, \Delta\gamma, \Delta n_z/V_0, \Delta\alpha, \Delta v/V_0, \Delta\theta, \Delta q)^T$. Δv, $\Delta\alpha$, $\Delta\theta$, Δq, Δh, $\Delta\gamma$, Δn_z are the disturbances of velocity, angle of attack, pitch angle, pitch rate, height, flight path of angle and normal acceleration respectively. δ_e is the deflection of elevator, δ_{LEF} represents the deflection of leading-edge flap which hasn't been considered in carrier landing in this study, δ_{PL} is the control input of throttle and u_{wind} is the vertical velocity turbulence caused by carrier air wake. In this study, since angle of attack is disturbed by the vertical velocity turbulence so that the aerodynamic forces and moments are disturbed by the perturbation of the angle of attack, u_{wind} can be treated as an input and integrated in the aircraft model for simplicity. This is the only change compared with the model in [29]. The state space matrices A, B, C and D are listed in Appendix A. The state values at the trim point in this model are $\alpha_0 = 8.1°$ and $V_0 = 69.96$ m/s.

2.2. Autopilot

In order to design a stable and rapid control system which has resistance to several disturbances, ACLS is made up of autopilot, which contains inner loop and APCS, guidance control and guidance compensation. Inner loop improves the pitch rate response performance to enhance the longitudinal static stability. The pitch rate command and the aircraft states, which include angle of attack, normal acceleration and pitch rate, are used as inputs in autopilot system.

The inner loop control structure is shown in Fig. 1. The parameters can be designed are represented with $K_1 \sim K_6$ in inner loop. K_1 is the pitch rate command gain, K_2 and K_3 are the corner frequencies of the lead-lag filter, K_4 is the feedback loop gain, while K_5 and K_6 are the gains of proportion and integral in PI controller respectively. Lead-lag filter provides the amplification of the low frequency signal and the lead phase effectively, and it resists the high frequency signal in a degree. To solve the problem of structural mode interaction, a 2-order structure filter is adopted to eliminate adverse effects of the lowest frequency structural mode and all higher structural mode frequencies [1]. The position and rate limiters make elevator deflect within the position and rate limitations. The models of structure filter, elevator, position and rate limiters, and pitch rate sensor refer to [1], [30], [30] and [31] respectively.

The function of ACT is implemented by the APCS which is shown in Fig. 2. The parameters that need to be designed are represented with $K_7 \sim K_{11}$ in APCS. To satisfy the requirement of design criterion, angle of attack α, normal acceleration n_z and pitch rate q are selected as the feedback signals in APCS, while the pitch rate command is the feedforward signal. Furthermore, one rate limiter and three position saturations [32] are induced in APCS to make signals not to exceed the allowed range. To prevent the frequent reversal phenomenon of throttle command, four low pass filters [32] are adopted to filter the high frequency signals in several control channels.

The structure of longitudinal autopilot which incorporates inner and APCS is shown in Fig. 3. K_{12} is normal acceleration feedback

Please cite this article in press as: Z. Yang et al., Automatic Carrier Landing System multilayer parameter design based on Cauchy Mutation Pigeon-Inspired Optimization, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.06.013