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Research on Control Strategy Development of Aircraft Automatic Landing System

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ABSTRACT

The automatic carrier landing system(ACLS) is a powerful support to ensure the combat effectiveness of the carrier, and its control strategy design has always been the most important research of the ACLS. The carrier-based aircraft is affected by the carrier air-wake and the motion of the carrier deck in the final approach , which improves the requirements for the track control and attitude keeping ability of the ACLS. Therefore, the design of the control strategy of the ACLS needs to consider the improvement of the tracking ability to the glide path for the ACLS in the final approach. This paper introduces the basic structure of the ACLS, and summarizes the future development of control strategy by analyzing the current research situation of control strategy .

1. Introduction

In 21st century，military power as a symbol of great power status, ensuring the legitimate rights and interests of the country and the safety of people's lives and property. Naval combat capability has always been an important criterion for measuring a country's military strength, and aircraft carrier at the core of the sea fleet has always been an important guarantee of naval warfare capabilities. The combat modes of aircraft carriers are mainly divided into attacks on surface and underwater ships, long-range attack on subgrade targets and control of air and sea control.

1.1 Research significance

How to improve the success rate of carrier-based aircraft approach and landing mission has always been the research focus of naval key technology. The approach and landing process of carrier aircraft is usually described as "dancing on the tip of the knife" or a controlled high-speed fall, aircraft pilots also has been dubbed the "dancers on point", this is because the aircraft pilot approach the ships during the mission in the implementation of the risk is much higher than ordinary pilots. The U.S. Navy statistics the accident and time of carrier-based aircraft during take-off and landing, as shown in Fig 1. According to the figure, it can be seen that the time of carrier-based aircraft approaching and landing only accounts for 4% of the flight time of carrier-based aircraft, but its accident rate is as high as 44.4%, of which the landing stage time is only 1%, but its accident rate reaches 20.1%. It can be seen that the closer to the tail of the aircraft carrier landing deck, the higher the probability of accidents on the carrier aircraft.

The stages of carrier-based aircraft approach flight process are divided as shown in Fig 1.3. The equiangular descent stage before carrier-based aircraft landing is usually called the approach landing stage, that is, the "FINAL APPROACH" stage in Fig 2. At the same time in the study of aviation spacecraft control strategy,and aircraft in the process of ship more similar aircraft landing problem also has always been the focus problem experts. However, compared with the landing of aircraft, the approach and landing of carrier-based aircraft is more difficult to control, requires higher precision and has more accidents. This is because the approach and landing methods and influencing factors of carrier-based aircraft are different from those of general land-based airports, the approach and landing of carrier-based aircraft is aimed at the aircraft carrier in motion and is affected by sea surface surge,at the same time the aircraft carrier deck for aircraft landing space is limited, the length of the landing deck is generally between 220 meters and 270 meters, which is less than one tenth of the landing runway of the onshore airport. The reduction of landing area leads to the difficulty of carrier-based aircraft entering and landing, and at the same time increases the operating load of carrier-based aircraft drivers(e.g. Wang L et al, 2016).

In the actual case of the carrier-based aircraft of the US Navy aircraft carrier, when entering the "FINAL APPROACH" stage, the F/A-18A carrier-based aircraft must keep the approach track, approach angle of attack and approach speed stable through the continuous operation of the driver, finally, ensure that the carrier aircraft successfully "hangs the cable" to complete the mission of entering the ship. If there is no safe entry condition at this time,

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go-around operation must be carried out. In this process, the pilot of carrier-based aircraft has high operating load, difficult work and high accident risk rate. More importantly, the approach and landing tasks are usually carried out after the pilots of carrier-based aircraft have finished their daily training and combat tasks, and the fatigue of the pilots is more likely to lead to the failure of the approach and landing tasks. In general, the mission time in the approach and landing phase is short, but it is the task that requires the highest operational accuracy of carrier-based aircraft drivers and has the highest driving risk coefficient.

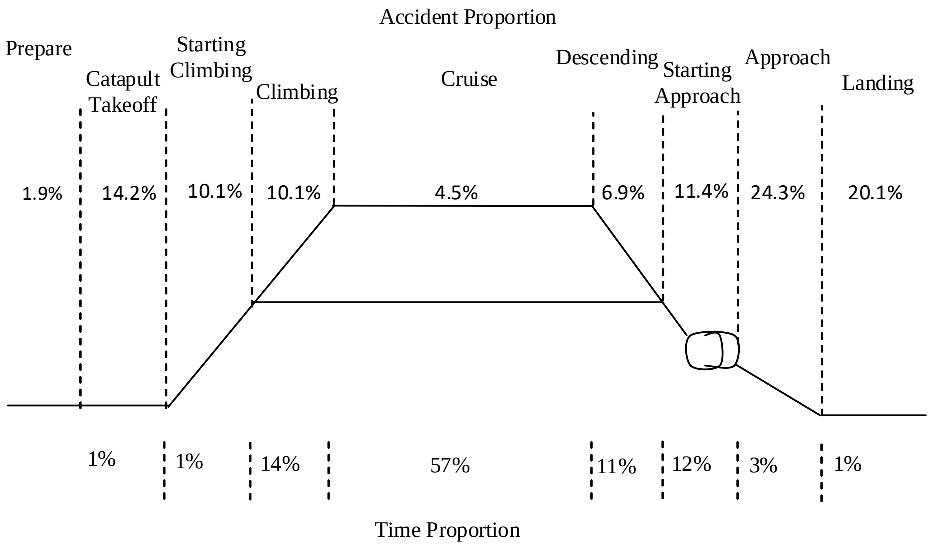

Fig. 1 Accident and time proportion of taking off and landing for carrier-based aircraft

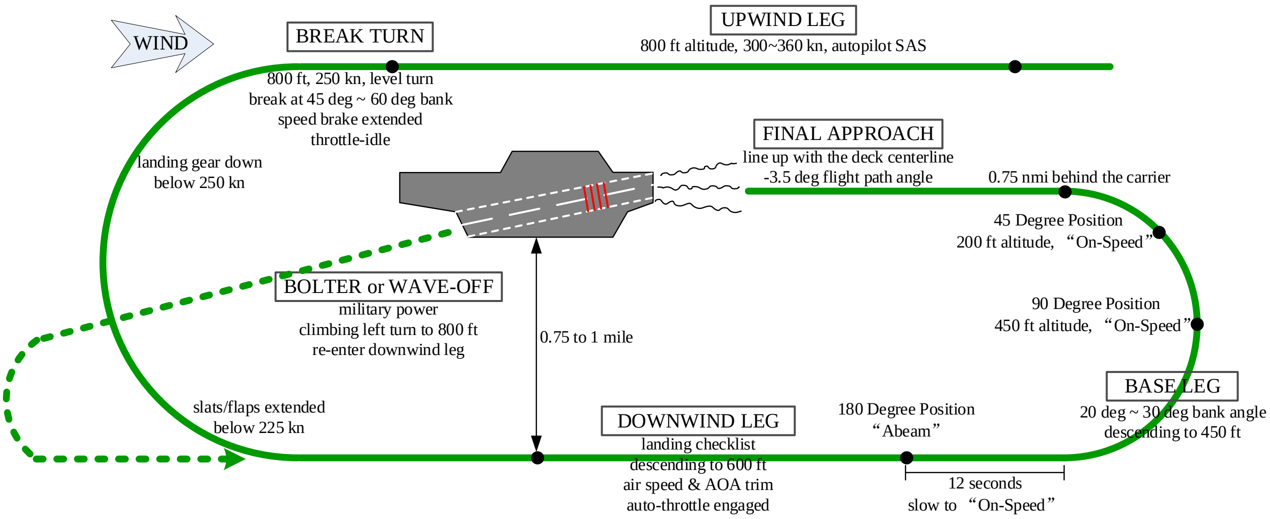

Fig. 2 Schematic diagram of the carrier landing flight phase for carrier-based aircraft

In order to solve the problems of carrier-based aircraft landing safety and cost consumption, the US Navy began to try to improve the carrier-based aircraft landing mode from the original carrier-based aircraft auxiliary landing mode to the automatic landing mode since 1948, and devoted itself to the development of the fully automatic landing system. The automatic landing system is composed of several subsystems, including flight control system, throttle control system, inertial navigation system, precision tracking radar and shipborne computer system, etc. Its purpose is to realize all-weather, all-sea conditions and automatic landing of carrier aircraft. With the development and application of automatic landing system for carrier aircraft, the system can significantly reduce the difficulty of landing by accurately controlling the approach and landing track of carrier aircraft, compared with the previous manual approach and landing methods, it has the following advantages:In terms of driver training, it can simulate the real landing environment，by training the pilot in the simulation environment, the training expenses of the pilot are reduced, so that the pilot can spend more precious training time on learning combat skills;In terms of carrier aircraft loss, it can reduce the impact load on the airframe structure, increase the service life of carrier aircraft, increase the number of available carrier aircraft and reduce maintenance costs; In terms of the safety of entering and landing, the number of decoupling from landing is greatly reduced, and the success rate of carrier-based aircraft entering and landing is improved; In terms of fuel consumption, the number of refueling aircraft in the air is reduced, and the number of aerial tankers on board is reduced. At the same time, there is no need to create conditions for the landing of carrier aircraft and sacrifice the maneuverability of the aircraft carrier too much, and can reduce operating costs, etc(e.g., Xia G et al., 2015; Urnes J M et al., 1981; Steinberg M et al., 1992).

2. The structure of the ACLS

The approach and landing guidance of carrier-based aircraft in the automatic landing system of carrier-based aircraft is divided into the following steps：

First step：Capture aircraft carrier tracking radar and ship to stage in the continuous tracking, carrier-borne machine angle and distance information, at the same time through the carrier-based aircraft carrier motion measurement device for the carrier roll motion, pitch, yaw movement and heave motion information;

Step 2: Need to get in front of the guidance law calculated aircraft in the point of origin to the ideal carrier aircraft carrier accurate coordinates of the inertial coordinate system, need stability through data processing at this time the carrier motion information and aircraft information separation;

Step 3: The shipboard computer according to the tracking error and carrier information by law to calculate the approach the guidance law, and through the data chain transmitter send aircraft guidance law of information and the tracking error;

Step 4: Aircraft through the data receiver to receive information and decoding,the decoding of the ship to guide the law of information transmitted to the aircraft flight control system, control the shipboard wing surface deflection can realize accurate tracking of ideal glide path.

In the process of approach and landing, the compensation calculation of aircraft carrier deck motion is introduced because in the phase of aircraft carrier tail hook need to hang a rope with cables, this requests the aircraft approaching the stage of ship movement, consistent with the aircraft carrier deck motion can reduce in the ship to overshoot rate to ship accidents. Aircraft automatic carrier landing system device as shown in Fig 3, mainly divided into two parts, shipborne and airborne equipment. Some shipboard devices are composed of tracking radar, aircraft carrier motion measuring device, display station, track recorder, guidance law computer, data link monitor and data link transmitter. Airborne part device enhanced by radar tracking system, data chain of receiver and flight control system, the automatic flight control system is divided into the gas system, the autopilot and coupler. At present, the configuration mode of U.S. automatic landing system is F/A-18E/F fighter with AN/SPN-46. The following describes the main devices of the automatic landing system.

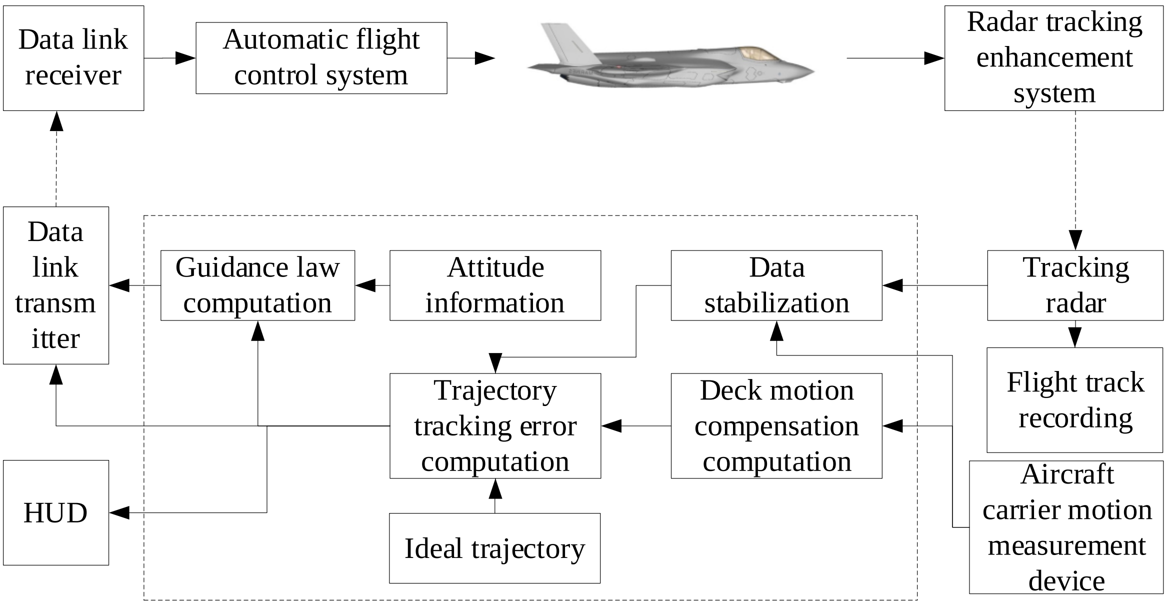

Fig. 3 Structure of ACLS for carrier-based aircraft

（1）Tracking radar

The current U.S. Fielding AN/SPN-46 automatic carrier landing system is the monopulse tracking radar used precision tracking radar measurement, the device can be AN-APN-202 type with airborne radar tracking enhance the system complete aircraft in the rectangular window position measurement, in front of the rectangular window unfinished tracking controlled by computer, after found tracking target by tracking the transmission system to control the finish of target tracking and measuring the distance to the device coordinates, elevation angle and azimuth angle.

(2) Aircraft carrier motion measuring device

The aircraft carrier motion measurement device mainly measures the aircraft carrier motion state information under the influence of unknown sea surface motion, and mainly assists the tracking radar in data stabilization processing and deck motion compensation calculation. Data stabilization processing is because the tracking radar will be affected by the unknown sea movement with the aircraft carrier when measuring the position coordinates of the carrier aircraft, so it is necessary to complete the data stabilization processing before calculating the trajectory error by using the position information. Deck motion compensation calculation is because the aircraft carrier motion is affected by the sea surface motion, need to compensate the deck motion and complete the trajectory error calculation.

(3) Guidance law computer

Ship-borne guidance law computer is the main device of ship-borne equipment in automatic landing system, and its purpose is to complete the calculation of glideslope guidance law of carrier-based aircraft. The carrier-based guidance law computer needs to calculate the carrier-based aircraft glide slope guidance instruction according to the carrier-based aircraft position coordinates provided by the tracking radar and the aircraft carrier motion information provided by the motion measuring device, and control the carrier-based aircraft to safely approach and land along the ideal glide slope.

（4）Data link transmitter

The task of the data link transmitter is to transmit the carrier-based glideslope guidance instruction and trajectory error instruction to the airborne data link receiver in the form of carrier signal by frequency shift keying in the UHF band, and transmit the identification code for verification. In order not to be confused with other data links and affect the approach and landing of carrier aircraft, Link-4A tactical data link is selected as its data link.

（5）Radar tracking enhancement system

In order to ensure the safe and smooth approach and landing of carrier aircraft, the radar tracking information accuracy of automatic landing system has high requirements. The main function of radar tracking enhancement system is to improve the measurement accuracy of tracking radar in combination with AN/SPN-46. The radar tracking enhancement system can counteract the influence of radar flicker through the high-energy pulse signal sent out somewhere in the fuselage under severe weather conditions such as cloud, rain and sky, and ensure that the tracking radar is not affected by the weather.

（6）Data link

Data link selection RT-1379 data link mainly includes data link receiver, frequency synthesizer, serial-parallel converter and analog-to-digital converter. Its function is to receive and decode the carrier signal transmitted by the data link transmitter, and obtain the glide slope guidance instruction and trajectory error instruction of the carrier aircraft.

（7）Automatic flight control system

Flight control system is generally composed of two flight control computer, airborne sensors and the driver's operation to calculate the rudder control system for the aircraft surface deflection angle, all kinds of flight control program is stored in the flight control system of programmable read-only memory. In the process of aircraft approach the ship, the flight control system can get through the data chain after decoding aircraft glide path guidance instructions and trajectory error control aircraft along the ideal glide path in the ship, aircraft safety in the ship.

3. The development of control strategy for the ACLS

With the wide use of automatic landing system in the process of approach and landing, in order to achieve accurate tracking of the ideal glideslope, the research on the control strategy of automatic landing system has gradually attracted the attention of researchers at home and abroad.In recent years, the research on control strategy of carrier-based aircraft automatic landing system is mainly divided into linear control strategy and nonlinear control strategy, and its specific classification is shown in Fig 4. Linear control strategy is divided into PID control and active disturbance rejection control. Nonlinear control strategies can be divided into sliding mode control, nonlinear dynamic inverse control, adaptive control, robust control and inversion control.Sliding mode control is the most widely used nonlinear control strategy, which can be combined with inversion control, adaptive control and nonlinear dynamic control, and significantly improves the tracking ability of automatic landing system to ideal glide slope. Intelligent control algorithm is also widely used in the control strategy design of automatic landing system. Because the automatic landing system is one of the flight control systems, its design scheme is similar to that of the automatic landing system. Therefore, the control strategy research of automatic landing system and flight control system also has certain reference value for the control strategy research of automatic landing system, which is also analyzed here.

Among linear control strategies, PID control strategy is the main applied control strategy at present. In reference(e.g., Nho K et al., 2000), a fuzzy controller is designed for automatic landing system, and the fuzzy control system is simulated and tested on a six-degree-of-freedom nonlinear aircraft model, the results show that the fuzzy control system has good robustness and is very suitable for controlling the flight path of aircraft during landing. The fuzzy control system is used to the longitudinal automatic landing system of carrier aircraft, and designs fuzzy controller for autopilot and power compensation system based on conventional PID control strategy. Compared with the conventional PID control strategy, the design has better tracking ability to the ideal glide slope. In reference(e.g., Yu Y et al., 2017), the disturbance rejection control combined with attitude controller and state observer is used to realize the compensation of disturbance flow in the approach and landing stage of automatic landing system.

Automatic carrier landing system linear control strategy of faultsare detailed, as a result of these design methods are mainly based on the linear method to carry on the design, although the linear method is relatively complete and easy to implement, but the model plane is actually nonlinear, the linear control strategy of control system in balancing point simulation may reduce model matching degree and the resulting deviation. At the same time, in the ship environment model of nonlinearity, complexity and strong coupling can improve the robustness of automatic carrier landing system and track correction ability request, this is linear control strategy is difficult to guarantee. Nonlinear control strategy in recent years, more and more used in the automatic carrier landing system design.

Feedback linearization has always been an important means to analyze and design nonlinear systems, the central idea of this method is to transform the nonlinear dynamic system into a completely or partially linearized system to realize feedback control. However, feedback linearization is completely different from the traditional linearization based on Taylor series, the main difference is that feedback linearization is accurate, not approximate. It only transforms the model into a linear model by selecting appropriate inputs, similar to transforming the physical model into its corresponding model by selecting appropriate state variables. This idea is also one of the shortcomings of feedback linearization, and this method has high requirements for the accuracy of the model. In reference(e.g., Menon P K et al., 2015), the nonlinear dynamic model of the system is transformed into linear time-invariant form by feedback linearization, and then the robust optimal guidance law is derived by finite interval differential. Which used the feedback linearization method to design the aircraft automatic landing system controller(e.g., Biju et al., 2007), considering the "surface effect" that you might encounter in the process of landing is adjusted to the controller, the simulation results prove the feasibility of the design scheme, and using feedback linearization to design the automatic landing system can ensure the glide path of ideal trajectory has good tracking ability. But the shortcoming of feedback linearization method is also very obvious, this method requires accurate mathematical model of the object, and this seriously limits the application of the feedback linearization method.

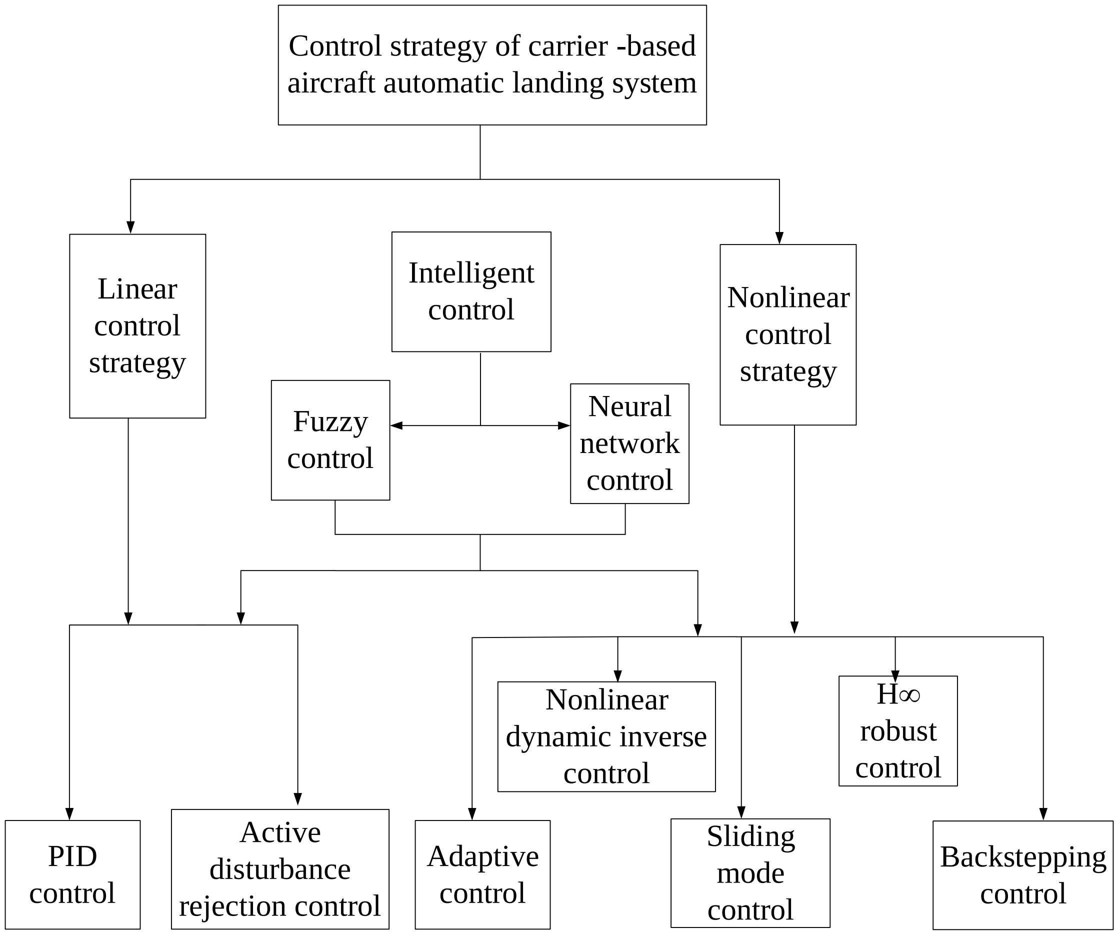

Fig. 4 ACLS control strategy classification

Nonlinear dynamic inversion can also be seen as a kind of feedback linearization of nonlinear system, by the layered model of the controlled nonlinear system is to invert the linear transfer function between input and output. In recent years, the nonlinear dynamic inversion is widely used in the design of flight control system. Paper on the basis of the nonlinear dynamic inversion method by combining neural network adaptive learning error compensating system model, the simulation results show that the method can well solve the problem of model error and the accurate control of the ideal glide path problem. Which used the nonlinear dynamic inverse method to design the outer loop of aircraft control system to ensure that the stability and tracking performance of the aircraft can be well maintained when faults occur and aerodynamic response changes(e.g., James R F et al., 2004). And method which adopted the nonlinear dynamic inverse method to design the automatic landing system of UAV solves the landing control problem of aircraft under given disturbance. Paper (e.g., Guan ZY et al., 2018) nonlinear dynamic inversion method is applied to design the automatic carrier landing system internal and external control circuit and power compensation system, implemented in error interference under precise control. But the disadvantage of using nonlinear dynamic inversion controller design is also very obvious, when the mathematical model of controlled object is uncertain, hard to ensure the robustness of system. For the flight control system with nonlinear dynamic inverse design, modeling errors and component failures will cause the system performance to deviate from the ideal flight state, in which case the response of the flight control system with nonlinear dynamic inverse design is unpredictable. Although the pilot can operate manually enough to keep the aircraft in flight, the aircraft may generate additional transient response to the pilot's command, resulting in the aircraft losing control.

Since the 1980 s, the robust control received extensive attention of the researchers, the purpose of which is under the affected by the uncertainty of the controlled object design controller can satisfy the demands of system robustness,H∞ control have been the core of the robust control research. H∞ control can solve the problem of H∞ minimum norm of transfer function matrix under external disturbance. In the design of control system, H∞ norm of transfer function matrix is used as performance optimization index, and then the optimal control law is obtained by minimizing H∞ norm.In reference(e.g., Subrahmanyam M B et al., 2012; Urnes J M et al., 1985), aiming at how to solve the uncertainty of carrier-based aircraft error disturbance, H∞ robust control strategy is adopted in the design of automatic landing system carried by F/A-18A carrier-based aircraft. The purpose of this design is to maintain a constant descent approach track under the influence of vertical gust and sensor noise in the process of carrier-based aircraft approaching and landing, and the system can respond well to vertical rate command. However, when the high-order transfer function is involved, the H∞ control strategy will make the high-order system more complex. For the design of automatic landing system, when its controller involves high-order transfer function, the H∞ control strategy may not be able to accurately track the ideal glideslope.

Since 1950s, adaptive control has been an important field of academic research on control problems, and its role is becoming more and more important with the development of adaptive control. This method means that the controller adopts adaptive control method for the controlled system with variable parameters or initial uncertainty. Adaptive control is different from robust control, it does not need to determine the bounds of these uncertain or time-varying parameters first, but robust control needs to ensure that these changes are within the given bounds. In terms of control law design, robust control does not need to change the control law, while adaptive control cares about the change of the control law itself. In reference(e.g., Sobel K M et al., 1982), adaptive control is used to design the longitudinal stability augmentation system of aircraft, and the results show that the stability of aircraft is obviously improved after adaptive control. Document adopts adaptive control to design flight control system for aircraft fault state. The simulation results show that compared with the conventional design, the adaptive controller in this design can better adjust the flight path in the aircraft fault state. However, the shortcomings of adaptive control are obvious, when the nonlinear model changes obviously, the controller parameters can not be adjusted in time. Therefore, adaptive control is often used in combination with robust control, inverse control and sliding mode control.

Sliding mode control can be regarded as a robust control method, which can switch from one continuous structure to another in state space, so it is also a variable structure control method. When designing the sliding mode controller, it is necessary to force the nonlinear system to move according to the designed sliding mode according to the state of the system and the purpose of the controller. Paper(e.g., Rao D V et al., 2013) uses sliding mode control to design the controller of aircraft automatic landing system. In this method, the deviation of the space position from the ideal flight path is transformed into a state variable and a sliding mode function is established, the simulation results show that the design can ensure the aircraft to accurately track the ideal glide slope during landing. Paper(e.g., Juang J G et al., 2015) in the sliding mode control design of the automatic carrier landing system combined with neural network controller, this design not only can effectively improve the anti-jamming ability of automatic carrier landing system, and realizes in harsh environments for the safety of the aircraft carrier landing guidance. Sliding mode control is widely used in flight control system design because of its fast dynamic response, insensitivity to parameter changes of controlled objects and small external interference.

Inversion control theory was used to design the stability control technology of a special nonlinear dynamic system in 1990. Inversion control is to reduce the order of high-order nonlinear dynamic systems and express them by low-order systems. These low-order subsystems can be stabilized by Lyapunov function and other methods. At the same time, this structure can ensure the designer to design from the known stable subsystem, and gradually design the controller that can stabilize each external subsystem, so as to achieve the stability of each external subsystem, thus completing the purpose of stable control and regulation of nonlinear dynamic system. In recent years, more and more researchers have adopted inversion control to design flight control systems.

Paper(e.g., Zheng F Y et al., 2015) proves that the landing environment has a great influence on the longitudinal distribution of ideal landing points and the stability of ship speed by analyzing the influence of landing environment on the aerodynamic characteristics of ship-borne UAV. To solve the environmental factors on the ship speed stability and track is precisely control the influence of the backstepping method is used to design the uav automatic carrier landing system, the simulation results proved that the inverse controller under the external environment factors interference, maintain the approach speed stability and resolves the problem of the precise control of the tracks. Paper(e.g., Sonneveldt L et al., 2015) mainly studies the application potential of the combination of backstepping control technology for nonlinear model and online model identification in the design of modern fighter flight control system. Through backstepping control to achieve the closed-loop state of the global asymptotic stability and tracking. Based on the nonlinear dynamic model of F-16 fighter, numerical simulation is carried out by using inverse flight controller. The design is compared with linear control strategy and nonlinear dynamic inverse control strategy, and its flight performance is compared by numerical. The results show that the flight control system designed by inverse control has significant performance improvement compared with nonlinear dynamic inverse control strategy and linear control strategy. Paper(e.g., Ju H S et al., 2008) based on adaptive inverse control of unmanned aircraft automatic landing system controller was designed, the results show that the design can effectively guide UAV to land along the ideal glide slope under the influence of gust disturbance. Paper(e.g., FARRELL J et al., 2003) based on the nonlinear model of aircraft, the main control framework is designed by using backstepping control, and a new control structure is proposed to keep the angle of attack constant. This structure can be used to improve the stability of approach and landing stage, and the unknown disturbance can be estimated by using the output state observer.

4. Conclusion

The precision demand of the ACLS which is designed by the feedback linearization method and the nonlinear dynamic inversion is higher. And it's hard to guarantee the system robustness in the influence of the modeling error and uncertainty landing environment, so the H∞ control strategy can increase system complexity. The backstepping control with sliding mode control can effectively solve the high order system of precise control and robust control problems, this method gets more attention of the researchers in the flight control system design, it has been widely used for the ACLS of the carrier-based aircraft and unmanned aircraft. Through the research and analysis of the control strategy of the ACLS, it can be seen that the design of its control strategy is a work with great use value and theoretical depth.

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