Unmanned Aerial Vehicle Flying Qualities Flight Test Evaluation Technique in Approaching and Landing Phase

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Abstract. Unmanned Aerial Vehicle (UAV) flying qualities in approaching and landing phase relates directly to flight safety. In this paper, autonomous control mode and remote piloted control mode were introduced for analysing approaching and landing flying qualities firstly. Then evaluation criteria about landing flying qualities of these two control modes were proposed according to characteristics and design requirements of UAV and manned aircraft flying qualities specifications. For autonomous control mode, control accuracy and transient response were the main contents of evaluation, but for remote piloted control mode, flight test evaluation method was given in order to lower risk and improve safety, which includes modified Cooper-Harper Rating Scale, closed-loop ground simulation, simulated approaching and landing flight test in low altitude and simulated remote piloted control landing flight test. Finally, flight test was carried out to demonstrate the validity of evaluation criteria and method which is useful and meaningful for UAV landing flying qualities evaluation.

1. Introduction

With the rapid development of flight control and navigation technology, Unmanned Aerial Vehicle (UAV) technology has made a breakthrough. Development and application of UAV has drawn great attentions of all the countries in the world both in military and civilian. Nowadays, US has deployed Global Hawk, Predator and other types to execute Intelligence, surveillance, Reconnaissance (ISR) and strike missions [1], while other countries are also trying to develop their own UAV.

Currently, the accident rate of UAV is so high, which is 10~100 times than manned aircraft [2]. One important reason, which causes high UAV accident rate, is lack of comprehension and inadequate research of UAV flying qualities. Moreover, understanding on concept of UAV flying qualities remain on the understanding of manned aircraft flying qualities and evaluation method and criteria still follow and use manned aircraft evaluation techniques, which does not reflect characteristics of UAV.

In recent years, domestic and foreign experts and scholars conduct study of characteristics of UAV flying qualities, while UAV airworthiness regulations has been issued to promote development of UAV. Mitchell et al [3] redistributed the flight phases of UAV, according to accuracy and rapidity of UAV flight mission. Ding Tuanjie et al [4] analysed influence factors affected UAV remote control mode and proposed preliminarily flying qualities evaluation method using manned aircraft flying qualities specifications. Pan wenjun et al [5] and Wang Feng et al [6] considered characteristics of UAV and manned aircraft flying qualities evaluation methods, analysed fundamental manned aircraft flying qualities requirements including static stability, modes characteristics and time-delay and the applicability of several typical piloted flying qualities requirements like the CAP and the Bandwidth.
criterion for UAV. Then some effective suggestions were presented. Wang Feng [7] studied landing flying qualities under remote control mode from the perspectives of time-delay and control mode.

Approaching and landing is one of the most accident prone phases of UAV. In this paper, autonomous and remote control mode for UAV approach and landing are introduced firstly which affects flying qualities evaluation. Then flying qualities evaluation criteria are proposed based on characteristics of UAV and UAV flying qualities flight test method is given. After analysing test results, the UAV flying qualities evaluation flight test method is proved effective, which is helpful and meaningful for UAV flying qualities research.

2. Approaching and landing control mode
There are several recovery modes for UAV, including parachute, arresting net, wheel landing and so on. For large and medium sized UAV, wheel landing is the main way for approaching and landing. Nowadays, manned aircraft landing is heavily depended on pilot and auto-landing system is just an auxiliary system, but UAV landing mainly operated by autonomous control system. However, due to complexity of operation, high level of risk and technical maturity, remote piloted control mode would be more useful and helpful for approach and landing in emergency circumstances which need to return to base. Hence, remote piloted control mode would usually be set as standby control mode in order to ensure flight safety. In this section, the theories of autonomous control landing and remote control landing would be introduced briefly.

2.1. Autonomous Control Landing
The most common Auto-control landing systems include Instrument Landing System (ILS), Microwave Landing System (MLS), and Global Position System (GPS). In this paper, the main consideration for auto-control landing is navigation information based on GPS. After finishing missions, flight control system of UAV would control the vehicle on the basis of location information provided by GPS, and approach and land according to pre-planned flight path.

There are six segments for UAV approaching and landing under auto-control landing mode, including initial approach, capturing and gliding, guiding and gliding, level off, heading aligning and landing, shown in figure 1. Auto-control system has two subsystems, longitudinal control system and lateral control system. Control method in every segment is shown as follows:

- Initial approach segment: After finishing tasks, UAV enter landing path. At specified height, landing gear and flap were down, and then UAV maintains this altitude, adjust speed, control lateral direction and align to runway according to pre-planned flight path.
- Capturing and gliding segment: UAV aligns itself to runway in lateral direction, and enter into extension line gliding flight path in longitudinal direction.
- Guiding and gliding segment: UAV flies along pre-planned gliding flight path at steady speed, correct lateral deviation relative to runway centerline.
- Level off segment: when UAV glides to flareout altitude. Then pull up attitude and reduce speed, UAV will touch down in a small sink rate.
- Heading aligning segment: UAV adjusts longitudinal direction attitude and speed in order to land under proper conditions like appropriate pitch attitude and sink rate, aligns heading to runway in lateral direction and level off at roll attitude, which would prevent aircraft from overshothing the runway or prevent wing from scarping the runway.
- Landing and running segment: after touching down, UAV begins to slow down and brake. During touching down, flight control system control attitude in longitudinal direction and deviation in lateral direction.
2.2. Remote control landing
UAV remote control landing is similar to manned aircraft landing, which still depend on stick and rudder. The main difference is Situation Awareness. Manned aircraft pilot could get feedback from external environment, but UAV pilot control the vehicle in Ground Control Station (GCS) separated from UAV. Control instructions are transmitted via up-link to flight control system of UAV and all the condition of subsystems and status of UAV are transmitted through down-link to GCS. UAV Remote pilots see the aircraft through on-board sensors and cameras down linking information displayed on the screen of computer in GCS and could not get the same quality of feedback as a manned aircraft pilot feels such as visual weather, smell of smoke, and vibration of fuselage. The figure 2 shows the control flow of manned aircraft and UAV.

![Diagram showing control flow of manned aircraft and UAV](image)

**Figure 1.** UAV approaching and landing under auto-control landing mode

![Diagram showing control flow](image)

**Figure 2.** Control mode in manned aircraft and UAV

3. Flying qualities of autonomous control mode
The idea conditions for UAV autonomous control landing should meet the following requirements. Firstly, the direction of ground speed is the same as runway centerline which means the track angle is equal to runway heading. Secondly, the body axis of aircraft should be in accord with runway centerline that means the course angle should be equal to runway heading. Thirdly, the wing should maintain level and the roll angle is zero. Lastly, UAV should be glide along extension line of runway centerline, and lateral deviation is zero.

Now, there are no requirements and specifications about UAV flying qualities. Hence, the contents of UAV autonomous control landing flying qualities are mainly proposed based on most commonly used UAV design requirements, manned aircraft flying qualities specifications and flight control regulations. The contents of demonstration are as follows: 1) UAV should fly steadily in approaching
and landing phase. 2) During transition of configuration, transient response should be smooth and convergent in longitudinal, directional and lateral directions, 3) Control accuracy of UAV should meet requirements of landing safely and precision index should be determined.

For control accuracy, the concerned parameters should be considered from perspective of safe landing as follows, such as initial approaching altitude, longitudinal and lateral deviation in guiding and gliding segment, location of touch down point, sink rate, roll angle, course angle, etc. All accuracies of these parameters should be meet related requirements of control accuracy in approaching and landing phase. Figure 3 is flight test result of UAV autonomous landing. It can be seen that transient response is smooth during transition of configuration and landing phase. From flight test result, UAV landed safely and autonomously and the control accuracy satisfied requirements.

- Figure 3. UAV autonomous approaching and landing flight test

4. Flying qualities of remote piloted control mode

4.1. Flight test evaluation method

UAV remote piloted control mode faces great challenge for human factor in human factor. UAV pilot workload is increased due to all operations in GCS, and time-delay increases operating difficulty. So it is needed to fully evaluate pilot workload and system controllability. Then, modified Cooper-Harper Rating Scale was proposed to evaluate flying qualities according to characteristics of UAV and requirements, which is an effective tool for comprehensive evaluation rating by UAV pilot. Modified Cooper-Harper Rating Scale is shown in figure 4.

For UAV landing flying qualities of remote piloted control mode, demonstration flight test should be divided into three steps in order to ensure UAV flight safety. These tests are closed-loop ground simulation, simulated approaching and landing flight test in low altitude and simulated remote control landing flight test.
### Figure 4. Modified Cooper-Harper Rating Scale for UAV

#### Table: Pilot Assessment on UAV

| Pilot decisions | Difficulty                        | Pilot assessment on UAV performance of operation |
|-----------------|-----------------------------------|-------------------------------------------------|
| Yes             | **Very easy, highly desirable**   | Operator workload is minimal and desired performance is easily attainable. |
| No              | **Easy, Desirable**               | Operator workload is low and desired performance is attainable. |
| Yes             | **Fair, mild difficulty**         | Acceptable operator workload is required to attain desired performance |
| No              | **Minor but annoying difficulties** | Moderately operator workload is required to attain adequate performance |
| Yes             | **Moderately objectionable difficulty** | High operator workload is required to attain adequate performance |
| No              | **Very objectionable but Tolerable difficulty** | Maximum operator workload is required to attain adequate performance |
| Yes             | **Major difficulty**              | Maximum operator workload is required to bring error to moderate level, but maintenance of effort in primary task is not in question |
| No              | **Major difficulty**              | Maximum operator workload is required to avoid large errors and ensure flight safety |
| Yes             | **Major difficulty**              | Intense operator workload is required to accomplish task and ensure flight safety, but numerous errors persist |
| No              | **Improvement Mandatory**         | Instructed task cannot be accomplished reliably and flight safety cannot be ensured |

#### 4.1.1. Closed-Loop ground simulation

UAV closed-loop ground simulation usually uses GCS to conduct simulation, while GCS and UAV are connected by data link. So the simulation conditions are almost same as real flight, and UAV closed-loop ground simulation in GCS has high fidelity. The typical closed-loop ground simulation test environment is shown in figure 5. GCS collects operation instructions that are sent to flight control computer in UAV via uplink. After computation of flight control system, the instructions are sent to UAV control surface and engine control system. Then simulation test station of flight management system collects flight state and builds simulation model to calculate dynamic response of aircraft. All of these data are transmitted to GCS through downlink after fulfilment by flight control computer. UAV pilot operate UAV according to information displayed in screens of GCS afterwards. All of these procedures form closed-loop. UAV pilot and operator could know well the flight test procedure and develop risk management measures through closed-loop ground simulation.
4.1.2. **Simulated approaching and landing flight test in low altitude.** Before simulated remote piloted control landing flight test, simulated approaching and landing flight test in low altitude should be carried out due to safety consideration. Simulated approaching and landing flight test would be conducted in 1000 meters above ground level (AGL) in order to examine UAV time-delay, controllability and stability under remote piloted control mode. Moreover, UAV control mode would be switched to remote piloted control mode before aligning with runway, and then UAV would be controlled remotely by pilot to turn and align with runway. Furthermore, UAV glides to 625 meters AGL with 2.5° glide slope angle. When reaching 625 meters AGL, UAV was controlled to level off, which is the end of simulated approaching and landing flight test in low altitude.

**Figure 5.** Closed-Loop Ground Simulation Test Environment Diagram

4.1.3. **Simulated remote piloted control landing flight test.** After analysis, remote piloted control landing test has great risk. For flight test safety, UAV landing flying qualities flight test evaluation would be accomplished through simulated remote piloted control landing. The specific test plan is as follows. Firstly, before aligning runway, UAV pilot sends instructions via GCS to switch control mode from autonomous control mode to remote control landing mode. And then UAV pilot aligns UAV with the designated landing runway and controls UAV gliding along pre-planned gliding flight path to 50 meters AGL. When UAV reaches assigned altitude, UAV pilot controls UAV to go-around.

4.2. **Flight test results**

Considering significance of flying qualities evaluation to pilot briefing, 5 test pilots who have full of UAV flight experience were chosen to evaluate and rate according to test procedures. UAV test pilots give flying qualities evaluation and rates about approaching and landing under remote control mode according to flight test. Table 1 is the pilot evaluations used by Modified Cooper-Harper scale rating.

**Table 1.** Modified Cooper-Harper scale rating for test pilots

| Pilot | Longitudinal Control | Lateral Control |
|-------|----------------------|----------------|
| 1     | 5                    | 4              |
| 2     | 4                    | 4              |
| 3     | 5                    | 4              |
| 4     | 6                    | 6              |
| 5     | 5                    | 5              |

From table 1, it can be seen that the Cooper-Harper scale locates 4～6 in longitudinal Control, and 4～6 in lateral Control when pilot operate UAV under remote piloted control mode for approaching and landing. UAV pilot could control UAV well in longitudinal and lateral directions in landing phase, but the workload is high.
Figure 6. Simulated landing under remote piloted control flight test result

Figure 6 shows that UAV pilot could control UAV flight safety during approaching and landing phase, but frequent operation is needed to align runway and glide along gliding path, which does accord with the results of pilot evaluation on basis of Modified Cooper-Harper Rating Scale.

5. Conclusions
UAV landing flying qualities for autonomous control and remote piloted control were studied theoretically and practically in this paper. Flying qualities of landing in autonomous control mode was evaluated from several aspects, like control accuracy, stability and safety, while for flying qualities of remote piloted control mode, flight test was conducted step by step in order to reduce risk and ensure flight safety, including closed-loop ground simulation, simulated approaching and landing flight test in low altitude and simulated remote piloted control landing flight test. Then modified Cooper-Harper Rating Scale was proposed and used to evaluate landing flying qualities of remote piloted control mode. The results show that the flight test evaluation method given in the study is useful and helpful in evaluation of landing flying qualities of UAV.

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