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Aircraft-Pilot System Modeling and Pilot Control Behavior Research for Airdrop Task

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Abstract

Adverse aircraft-pilot coupling during the process of transport airdrop can lower the level of flight safety. Pilot's rational control behavior can avoid adverse aircraft-pilot coupling. In this paper, the model of aircraft-pilot system consisting of motion body model, task model and pilot model is built at first. Three different pilot control methods are investigated for airdrop. The first one is continuous pitch compensatory control, the second one is elevator maintenance control, and the third one is precognitive control based on the knowledge of flight tendency during airdrop. Two different precognitive control methods are designed. Models of those pilot control methods are constituted and numerical simulations are conducted. In addition, for exploration on feasibility of those methods, a series of pilot-in-loop real-time experiments are performed in a fixed flight simulator. Real-time experiments match well with numerical simulation results which validate different effects of those methods on airdrop. The aircraft performs most satisfactorily under the two precognitive control methods. The study is of considerable significance to investigate of which kind of pilot control method to be applied during airdrop.

Keywords: transport airdrop, aircraft-pilot system modeling, aircraft-pilot coupling, pilot control behavior .

1. Introduction

Transport aircraft is an effective vehicle for dealing with emergency. Cargo airdrop is one of the main applications of military transport aircraft. It also has practical applications in civil field. This paper focuses on heavy cargo airdrop[1]. Since high altitude airdrop is only available for light equipment or parachutists[2], low altitude airdrop reduces the vertical velocity of cargo and ensures good condition of cargo as well as a higher precision of airdrop field. Thus for heavy cargo airdrop, low altitude or super low altitude airdrop is the first choice. However, low altitude airdrop may be affected by complex atmosphere disturbance， which has great disadvantage on flight. A rational control of pilot can enhance the level of flight safety.

The mass, as well as the moment of inertia and the centroid of the carrier aircraft, changes during the extraction of cargo, and eventually leads to considerable deviations of flight states. Many studies have been conducted to this field, and dynamic functions are built to enhance those researches[3-4]. Numerical simulation of airdrop provides a better understanding of the whole airdrop process, and leads to a significant reduction of flight tests and costs[5-6]. At present, most of the studies focus on analysis and simulation of flight response or cargo motion. In the early 1990s, Baixian Fu computed the motion of continuous airdrop, and studied the responses of aircraft through a series of simulations[7]. The effects of different factors, i.e. cargo mass, pull coefficient, CG coefficient and initial flight condition, on the responses of flight states have also been studied[8,9].

A marked change of flight states may lead to sudden change of pilot operation. Unexpected Aircraft-Pilot Coupling (APC) may happen as a result[10-12]. Thomas J. studied the interaction between aircraft and pilot[13]. He presents a cargo airdrop simulation, which is a real-time environment in order to include pilot interaction. The conclusion is that only experienced pilot would probably be able to bring the aircraft quickly into a new trim state. An inexperienced pilot, however, can make the situation even worse by trying to compensate the deviations, and might lead to Pilot Induced Oscillation (PIO) problems. Leaving the controls as they are during airdrop is recommended as a result. There is not an effective method given by Thomas J. to control aircraft. However, the violent oscillation brought by airdrop needs to be controlled. Therefore, a simple, easy mastered method will be put forward in this paper to minimize the deviations of flight states.

2. Modeling of aircraft-pilot system for airdrop

In order to study the characteristics of aircraft-pilot coupling (APC) during the process of airdrop, the aircraft-pilot system is modeled at first.

The structure of aircraft-pilot system model shown in figure 1 includes three elements: motion body model, task model and pilot model. Each model's function is introduced in detail.

2.1. Motion Body Model

The Motion Body Model includes aircraft model and cargo model [14-15]. For investigating aircraft characteristics during airdrop, the aircraft's force equations and moment equations are built. The cargo's translation motion will affect aircraft's flight, so the cargo's force equations are also required.

Above models are given in Figure 1, where vectors $\boldsymbol{r}_\mathrm{a}, \boldsymbol{\Theta}_\mathrm{a}, \boldsymbol{v}_\mathrm{a}$ and $\boldsymbol{\omega}_\mathrm{a}$ represent aircraft's location, attitude, velocity and angular velocity. Vectors $\boldsymbol{r}_\mathrm{c}$ and $\boldsymbol{v}_\mathrm{c}$ mean cargo's location and velocity. Variety δ_e means elevator deflection of aircraft, which is controlled by pilot. Variety $\boldsymbol{F}_\mathrm{c}$ means the traction force of parachute to the cargo as the cargo moves out of the aircraft with the traction of a parachute.

2.2. Task Model

Task Model includes external condition and reference inputs of aircraft flight. The external condition gives all environment factors related to airdrop, for instance, airdrop field $\boldsymbol{R}$, weather and atmospheric turbulence $\boldsymbol{W}$. The pilot decides whether to start airdrop or not basing on both external condition and aircraft flight states $\boldsymbol{r}_\mathrm{a}, \boldsymbol{\Theta}_\mathrm{a}, \boldsymbol{v}_\mathrm{a}, \boldsymbol{\omega}_\mathrm{a}$.

The reference inputs of aircraft flight $\boldsymbol{r}_\mathrm{r}, \boldsymbol{\Theta}_\mathrm{r}, \boldsymbol{v}_\mathrm{r}, \boldsymbol{\omega}_\mathrm{r}$ are ideal flight states of the aircraft during airdrop. The pilot controls the aircraft flight according to these reference inputs.

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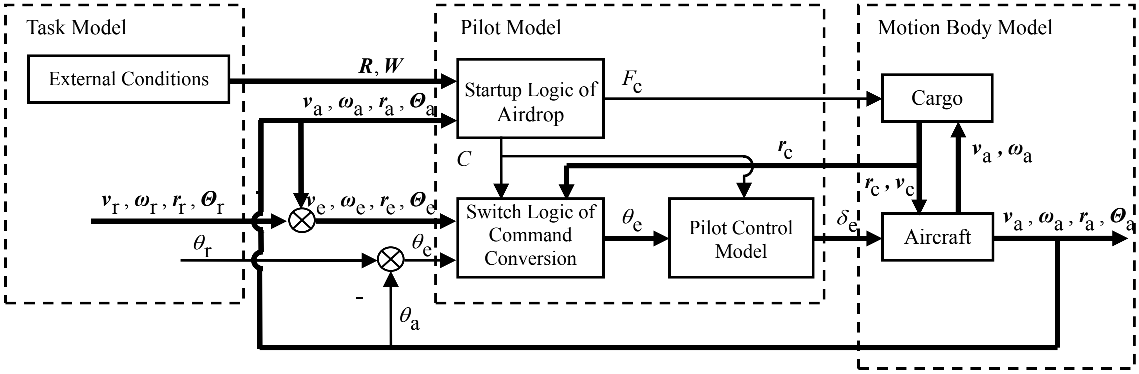


Fig 1 Structure of aircraft-pilot system model for airdrop

2.3. Pilot Model

Pilot Model describes pilot's control behavior during the process of airdrop. As shown in Figure 1, Pilot Model includes startup logic of airdrop, switch logic of command and pilot control model.

The startup logic of airdrop and the switch logic of command describe pilot's discrete decision-making behavior. During the airdrop pilot should decide the startup time T_1 for airdrop. Both the external conditions $\boldsymbol{R}, \boldsymbol{W}$ and aircraft flight states $\boldsymbol{r}_{\mathrm{a}}, \boldsymbol{\Theta}_{\mathrm{a}}, \boldsymbol{v}_{\mathrm{a}}, \boldsymbol{\omega}_{\mathrm{a}}$ are analyzed whether they are suitable for airdrop. The airdrop startup command is dictated when time is right. With the start of airdrop, the fixing device of cargo is released. The cargo moves out of the aircraft with the traction force of parachute $\boldsymbol{F}_{\mathrm{c}}$.

The switch logic of command decides the task command given to the pilot during different airdrop stages. The process of airdrop can be divided into three stages according to time sequence. The command of airdrop C and the position of cargo $\boldsymbol{r}_{\mathrm{c}}$ are used to distinguish each stage. The relationship between the time sequence of airdrop and the pilot's control task command is shown in Figure 2.

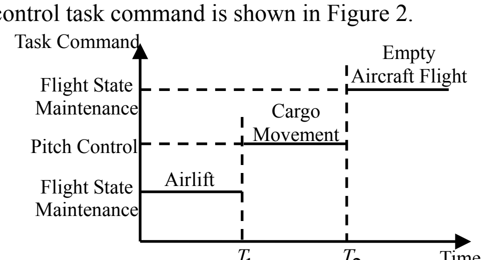


Fig 2 Relationship between the time sequence of airdrop and the pilot control task command

During the airlift stage, the aircraft remains initial flight states while the cargo is fixed in its initial position. Pilot's control task in this stage is to maintain straight level flight. The cargo movement stage begins when the pilot dictates the start of airdrop at time T_1. Traction parachute is released so as to pull the cargo toward the rear. Pilot's task in this stage is to avoid severe oscillation of flight state. The empty aircraft stage comes when the cargo moves out of the aircraft at time T_2. Then the pilot brings the aircraft back into a new straight level flight. Pilot's task in this stage is to maintain the new flight state.

At airlift stage and empty aircraft stage, pilot should control the aircraft to maintain straight level flight. The errors $\boldsymbol{r}_{\mathrm{e}}, \boldsymbol{\Theta}_{\mathrm{e}}, \boldsymbol{v}_{\mathrm{e}}, \boldsymbol{\omega}_{\mathrm{e}}$ between the reference inputs $\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{\Theta}_{\mathrm{r}}, \boldsymbol{v}_{\mathrm{r}}, \boldsymbol{\omega}_{\mathrm{r}}$ and the real flight state $\boldsymbol{r}_{\mathrm{a}}, \boldsymbol{\Theta}_{\mathrm{a}}, \boldsymbol{v}_{\mathrm{a}}, \boldsymbol{\omega}_{\mathrm{a}}$ are calculated and given to the pilot. Based on the errors $\boldsymbol{r}_{\mathrm{e}}, \boldsymbol{\Theta}_{\mathrm{e}}, \boldsymbol{v}_{\mathrm{e}}, \boldsymbol{\omega}_{\mathrm{e}}$, the pilot creates attitude control command θ_{e} and controls flight according to it.

The task for pilot on the cargo movement stage is to restrain oscillations of flight states. θ_{r} is the reference pitch during that stage. The pilot controls aircraft also depending on θ_{e}.

The pilot control model describes the pilot's control behavior basing on task instructions. Compensatory control, precognitive control or any other control methods can be used here. And that is the very part to be investigated in this paper.

3. Investigation of pilot control methods for airdrop

The startup logic of airdrop and the switch logic of command have been described in detail in Section 2.3. The pilot control model will be studied here.

3.1 Compensatory control

Compensatory control of pitch is introduced firstly that the pilot will do precise tracking of pitch during airdrop. Classical pilot model includes McRuer Model, Hess's Structural Pilot Model and Pilot Optimal Control Model (OCM). All of these models are quasi-linear models. During the process of airdrop, the characteristics of APC change suddenly when the cargo moves out. Above quasi-linear pilot model cannot be used to describe pilot's nonlinear control behavior.

While the aircraft characteristics changes with the motion of cargo, a time-varying structural model is essential. Such kind of pilot model and aircraft-pilot system have been studied by Ronald A. Hess [16,17]. At the airlift stage, a Hess's structural pilot model[18,19] Y_{p1} is used to describe pilot's continuous compensatory control behavior. During the cargo movement stage, the characteristics of aircraft change continually with cargo's motion. Generally, the cargo will move out of aircraft in 5 seconds which is a short time. Although pilot control behavior exhibits nonlinear characteristics, the structural model for airlift stage Y_{p1} is also used here. At the empty flight stage, another structural pilot model Y_{p2} is applied. The structure of pilot control model is shown in Figure 3, of which Y_{p1} is the structural model for airlift stage and also be used during cargo movement stage, while Y_{p2} is the structural model for empty aircraft stage. An adaptive time τ is needed for pilot to adapt well to new features of empty aircraft. So the time that S switches from 1 to 2 is set as $T_2+\tau$, where $\tau = 2\mathrm{s}$ [20].

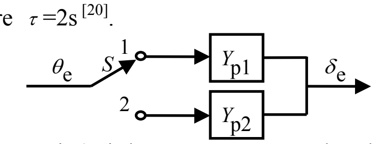


Fig 3 Pitch compensatory control model

At the airlift stage and the empty aircraft flight stage, the pilot controls the aircraft's pitch attitude to maintain straight level flight. Table 1 shows the parameters of the initial and final equalization flight states for airdrop task. These parameters are regarded as the reference inputs of aircraft flight.

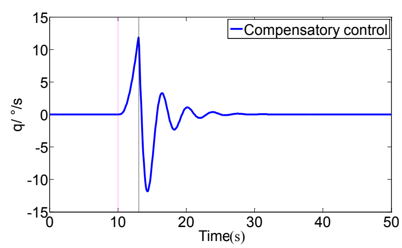
Table 1 Initial and final flight parameters

Item	Initial flight parameters	Item	Final flight parameters
$V_1(m\cdot s^{-1})$	100	$V_2(m\cdot s^{-1})$	100
H_1/m	800	H_2/m	800
$\alpha_1/(°)$	3.352	$\alpha_2/(°)$	2.040
$\theta_1/(°)$	3.352	$\theta_2/(°)$	2.040
$\delta_{e.1}/(°)$	1.931	$\delta_{e.2}/(°)$	5.719

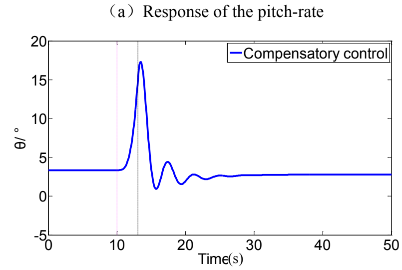
At the cargo movement stage, smoothly flight is hoped. The pilot obtains the attitude control command θ_e directly and controls the pitch attitude in order to eliminate the error of pitch θ_e.

The mass ratio of cargo to aircraft λ affects the APC characters of airdrop. In this paper, the mass ratio λ is set as 0.169.

The pitch compensatory control model is added to the aircraft-pilot system model and numerical simulation is conducted to test the effectiveness of the control method. Simulation results are as follows, where T_1=10 sec.



(a) Response of the pitch-rate



(b) Response of the pitch

Fig 4 Responses of flight states with compensatory control

Figure 4 shows the responses of aircraft during airdrop. With the motion of cargo, the aircraft will nose up and the pitch will increases at cargo movement stage. In order to eliminate the pitch deviation quickly, the pilot pushes the control stick to obtain a negative elevator deflection. This control behavior leads to the aircraft's nosing down, and as a result, the pilot pulls the control stick to obtain a positive elevator. During the process of airdrop, the pilot controls the stick repeatedly. Therefore, the aircraft flight states oscillate violently. It is very easy to bring pilot induced oscillation (PIO), just like illustrated by Tomas in reference [13]. Therefore, a more effective pilot control method is essential for the sake of safety.

3.2 Elevator maintenance control

The results above show that pilot's precise tracking of pitch during airdrop will lead to serious oscillations of flight states, and may also lead to PIO. It is well known that one of the causes of PIO is pilot's precise tracking behavior. If the gain of pilot control is higher, the aircraft-pilot system is more unstable. Additionally, the pilot controls flight states through the operation of elevator. Theoretically, a larger deviation of pitch needs a higher deflection of elevator to maintain flight states. Maintaining elevator deflection is one method to decrease pilot control gain. Hence, elevator maintenance is taken into account when designing pilot control methods.

As shown in figure 5, an additional maintenance module is placed after the pilot structural models. Variety δ_{e0} is defined as the value of maintenance.

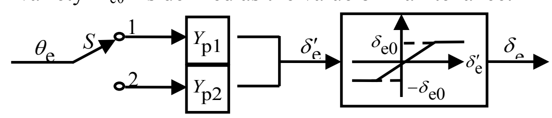
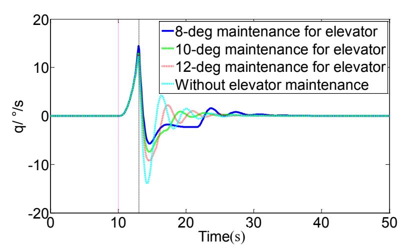
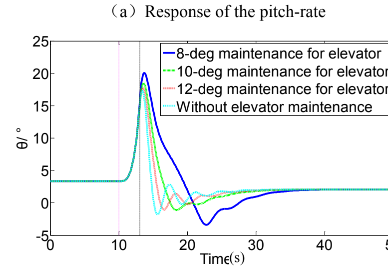


Fig 5 Elevator maintenance control model

The influence of elevator maintenance on responses of aircraft is investigated. The control stick provides the interface between pilot and aircraft which means maintenance of elevator can be translated to maintenance of stick displacement in practice. In this airdrop task, maintenances of elevator δ_{e0} are set as 8°, 10° and 12° separately. Responses of aircraft are shown in Figure 6, comparing with no elevator maintenance. Elevator deflection curve is shown in Figure 7.



(a) Response of the pitch-rate



(b) Response of the pitch

Fig 6 The effect of elevator maintenance on airdrop

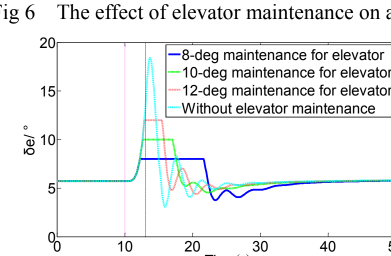


Fig 7 Elevator deflection of elevator maintenance

The main parameters of the responses of aircraft are given in Table 2. V_{emax} in Table 2 is the peak value of velocity deviation during airdrop. q_{max} is the maximum of pitch rate which is the peak value of nose-up rate. q_{min} is the minimum of pitch rate which is the peak value of nose-down rate. θ_{emax} is the peak value of pitch deviation. H_{emax} is the maximum of altitude deviation.

Table 2 Comparison of elevator deflection maintenance

Item	8°	10°	12°	No maintenance
$V_{e\max}/(m\cdot s^{-1})$	10.0	6.9	5.7	4.7
$q_{\max}/(°\cdot s^{-1})$	14.4	13.1	12.4	12.4
$q_{\min}/(°\cdot s^{-1})$	-5.7	-7.4	-9.3	-14.0
$\theta_{e\max}/(°)$	16.6	15.0	14.3	13.7
$H_{e\max}/m$	96	62	49	37

Flight curves in Figure 6 and data in Table 2 show us that maintaining elevator has some kind of influence on aircraft. For instance, $V_{e\max}$ rises to 10m/s from 4.7m/s, and $H_{e\max}$ rises to 96m from 36m when the maintenance of elevator is set as 8°. The loss of velocity and altitude is acceptable in the simulated mission. Figure 6 reveal that maintaining elevator has good effects on pitch since the $q_{\min}$ decreases from 14°/s to 5.7°/s and the oscillation of pitch has been dampened.

One can conclude from Figure 8 that maintaining elevator does not have noticeable influence on the motion of cargo.

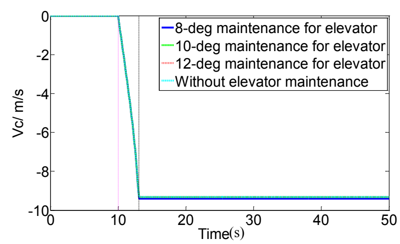


Fig 8 Effect of elevator maintenance on cargo motion

Though elevator maintenance control method has better effects than compensatory control, the simulation results are not that satisfying cause the deviations of flight states remains too large. Other control methods are needed to be designed.

3.3 Precognitive control

For an airdrop task, the start time of airdrop, the fixed position of cargo and cargo motion are known by pilot in advance. Hence an experienced pilot has a practical understanding of flight tendency during airdrop, i.e. the pitch will increase with the start of airdrop if there is no control. Precognitive control is introduced to decrease that change.

3.3.1 Precognitive control method 1

Pilot precognitive control method 1 for airdrop is designed as follows. First, do compensatory control on the airlift stage. Then increase elevator to δ_{e0} with the start of airdrop. The elevator kept constant when the cargo moves inside the cabin. The elevator turns back to pitch compensatory control to bring the aircraft into a new trim state when the cargo moves out.

Formula (1) describes the control method.

$$\delta_e = \begin{cases} Y_{p1}\times\theta_e & C=0 \text{ and } K=0 \\ \delta_{e0} & C=1 \text{ and } K=0 \\ Y_{p2}\times\theta_e & C=1 \text{ and } K=1 \end{cases} \tag{1}$$

Y_{p1} and Y_{p2} are the same with what we've got above. C represents the airdrop signal. C=0 at airlift stage and C=1 with the start of airdrop. K represents cargo's position while when K=0 means the cargo is inside the aircraft and when the cargo moves out of the cabin, K=1. A pilot model is built to realize the control method, shown in Figure 9.

According to the method, δ_{e0} should be given in advance. The mass of cargo is taken into account when design the value of δ_{e0}. The maximum of error of pitch $\Delta\theta_{\max}$ is set as optimization function.

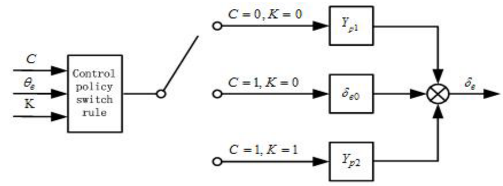


Fig 9 Pilot model for precognitive control method 1

Through a series of simulations, the relationship between $\Delta\delta_e$ and the ratio of mass of cargo to aircraft λ are as shown in Figure 10.

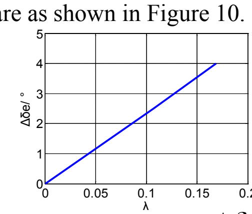
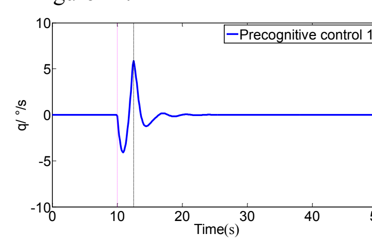
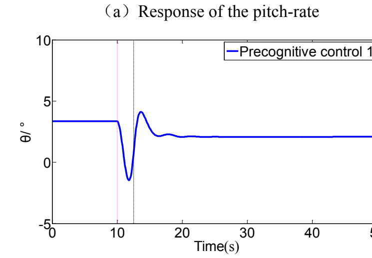


Fig 10 Relationship between $\Delta\delta_e$ and λ

In order to compare with the results of compensatory control method and elevator maintenance control method, airdrop simulation is conducted with $\lambda = 0.169$, and the responses of aircraft are shown in Figure 11. The elevator curve is shown in figure 12.



(a) Response of the pitch-rate



(b) Response of the pitch

Fig 11 Responses of flight states with precognitive control method 1

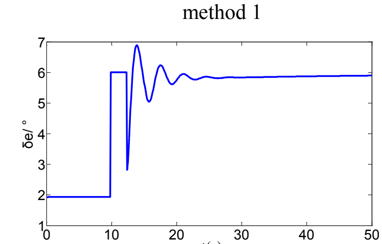


Fig 12 Elevator deflection of precognitive control method 1

Comparing with the first two control methods, all flight states have been controlled effectively under precognitive control method 1. However, the initial change of pitch is kind of large cause the value of δ_{e0} is a little big. Hence, precognitive control method 2 is designed as an adjustment.

3.3.2 Pilot precognitive control method 2

Pilot precognitive control method 2 for airdrop is designed as follows. First, do compensatory control on the airlift stage. Then increase elevator to δ_{e1} , a smaller value compared with δ_{e0} designed above, with the start of airdrop. The aircraft will nose down respectively and nose up with the movement of cargo. Increase elevator to δ_{e2} at the point of nose up and keep that until the cargo moves out. Turn back to pitch compensatory control to bring the aircraft into a new trim state when the cargo moves out.

Formula (2) describes the control method.

$$\delta_e = \begin{cases} Y_{p1} \times \theta_e & C = 0 \, and \, K = 0 \, and \, L = 0 \\ \delta_{e1} & C = 1 \, and \, K = 0 \, and \, L = 0 \\ \delta_{e2} & C = 1 \, and \, K = 0 \, and \, L = 1 \\ Y_{p2} \times \theta_e & C = 1 \, and \, K = 1 \, and \, L = 1 \end{cases} \tag{2}$$

Here L represents the signal of pitch. The initial value of L is 0 and L turns to be 1 at the point when the aircraft start to nose up during the movement of cargo in the cabin.

An pilot model is built to realize the control method, shown in figure 13. According to the method, δ_{e1} and δ_{e2} should be given in advance.

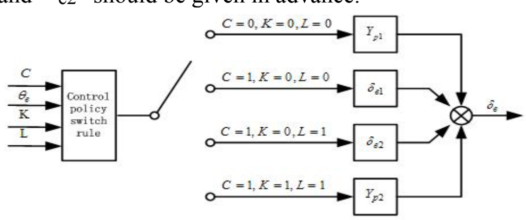
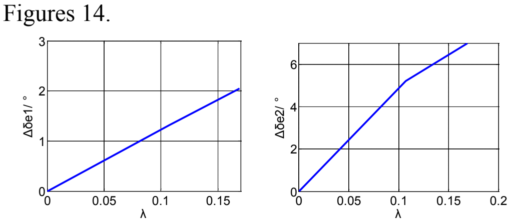


Fig 13 Pilot model for precognitive control method 2

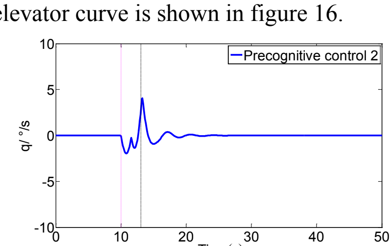
Two fit curves which describe the relationship between $\Delta\delta_{e1}$ and λ, else the relationship between $\Delta\delta_{e2}$ and λ are created respectively. The values of $\Delta\delta_{e1}$ and $\Delta\delta_{e2}$ for any λ can be picked in the Figures 14.



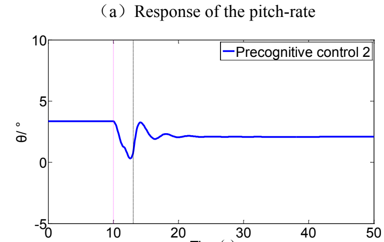
(a) $\Delta\delta_{e1}$ and λ (b) $\Delta\delta_{e2}$ and λ

Fig 14 Relationship between $\Delta\delta_{e1}$, $\Delta\delta_{e2}$ and λ

Airdrop simulation is conducted where $\lambda = 0.169$, and the responses of aircraft are shown in Figure 15. The elevator curve is shown in figure 16.



(a) Response of the pitch-rate



(b) Response of the pitch

Fig 15 Responses of flight states with precognitive control method 2

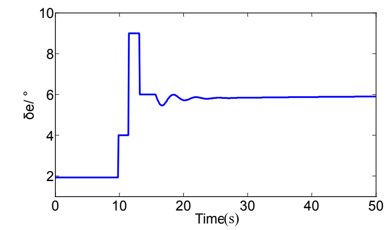


Fig 16 Elevator deflection of precognitive control method 2

The pitch problem of precognitive method 1 has been improved while the other flight states are basically remain the same. However, the disadvantage of precognitive method 2 compared with method 1 is its complexity which may lead to execution problem in practice. Comparing with the first two control methods, the aircraft performs most satisfactorily under the two precognitive control methods since all flight states have been controlled effectively.

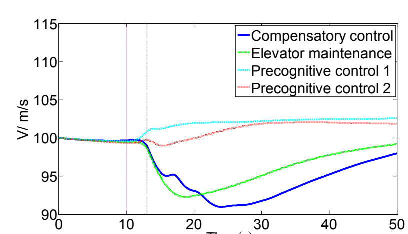
4. Real-time experiment with pilot-in-loop

In order to test those methods in practical use, pilot-in-loop real-time experiments are conducted. These experiments were fulfilled by use the BUAA (Beijing University of Aeronautics and Astronautics) fixed-based flight simulator for investigation of manual control task. The closed-loop pilot-aircraft system is shown in Figure 1 and the pilot model is substituted by a real pilot.

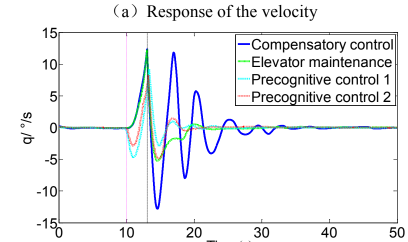
Experiment results are shown in Figure 17, which are in agreement with those methods designed above. Table 3 gives the comparison about the aircraft flight states between those methods.

Table 3 Comparison of flight data

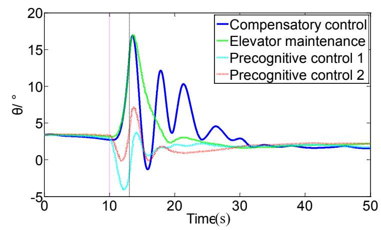
Item	Compen - control	Elevator maintenance	Precog- control 1	Precog- control 2
$Ve_{max} / (m \cdot s^{-1})$	9.0	7.7	2.6	2.1
$q_{max} / (^\circ \cdot s^{-1})$	12.8	12.3	9.0	8.3
$q_{min} / (^\circ \cdot s^{-1})$	-12.8	-5.2	-4.6	-4.9
$\theta_{e\max} / (^\circ)$	12.6	12.6	7.4	5.1
$H_{e\max} / m$	84.8	70.1	27.6	16.1



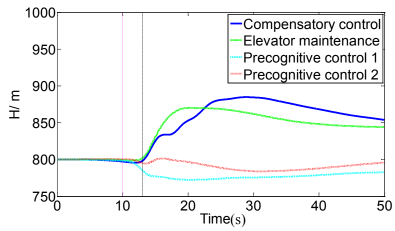
(a) Response of the velocity



(b) Response of the pitch-rate



（c）Response of the pitch



（d）Response of the altitude

Fig 17 Responses of flight states

Experiment results match well with numerical simulations, which illustrate that precise pitch compensatory control will lead to violent oscillations of flight states. The peak value of nose-down rate decreases when elevator maintenance is introduced, which dampens the oscillation effectively. Precognitive control executed by the pilot is based on the knowledge of flight tendency during airdrop. Both two precognitive methods are effective and each has its own advantages and disadvantages. Precognitive control can be easily mastered according to the real-time experiments and is comparatively more effective than the first two methods as both attitude oscillation and flight trajectory are well controlled.

5. Conclusions

(1) An aircraft-pilot system model is built with detailedly defined motion body model, task model and pilot model inside which can be used for investigating aircraft-pilot coupling during heavy cargo airdrop.

(2) Cargo's motion has remarkable influence on aircraft since the reaction of aircraft is violent. Precise pitch compensatory control is not suitable for airdrop and may lead to PIO problems.

(3) Three different control methods are investigated to control flight states during airdrop. There are obvious differences between those methods on flight. Precognitive control dampens the oscillations of flight states most effectively and simplifies complex command.

(4) Values of elevator operation for precognitive control are not the same when cargo mass changes. The relationship is given in the paper.

The study presents an effective control method which minimizes flight deviations and dampens oscillations during heavy cargo airdrop. The result is of considerable significance to be applied in practical use.

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