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Design of Aircraft Center of Gravity Control Law Based on Sliding Mode Control

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Design of Aircraft Center of Gravity Control Law Based on Sliding Mode Control

Jianing Yan, Jing Zhang and Haiquan Li

***Abstract*—A sliding mode based active center of gravity control law is designed for the aircraft with center of gravity varying during flight. As the basis, the general scheme of the active center of gravity control system is proposed, and the mathematic model of aircraft center of gravity varying with fuel transfer is established. Then, the center of gravity control law based on sliding mode control theory is designed, which can guarantee the control error converges to zero in finite time. Finally, simulations are carried out to verify the proposed method. Simulation results show that the sliding mode based center of gravity control law can accurately and rapidly track the given command for various different fuel transfer conditions.**

I. INTRODUCTION

The active center of gravity (CG) control is an advance technology to effectively reduce the trim drag and gain the potential economic benefits. The active CG control technology is usually based on a fuel transfer system which can transfer fuel among different fuselage tanks during flight and then adjust the aircraft longitudinal CG position [1].

In 1980s, the active CG control technology is firstly proposed [2-3]. Compared to the traditional CG control strategy, this advanced technology can change the distribution of the movable loads on the aircraft, such as the fuel in the fuselage and wings, in order to realize in-flight CG position adjustment as required, and greatly improve and optimize the flight performance of the aircraft.

In the aspect of active CG control technology, reference [4] put forward a standard weight and antifreeze balance scheme. This scheme integrates Airbus water balance strategy and Boeing standard weight balance strategy. By transferring the antifreeze and balance weight forward or aft, in-flight CG control is accordingly achieved. This synthetical CG control scheme mainly utilizes the manual adjustment type. Besides, reference [1] and [5] further investigate the automatic CG control strategy. The CG control law based on the disturbance observer [1], NCD optimization based PD control law [5] are respectively proposed to achieve in-flight precise control of aircraft CG position. However, for the aircraft CG control, the conditions of flight attitude variation and fuel consumption may bring obvious disturbances to CG, and then affect the control performance. Therefore, the advanced CG control law to solve the disturbance problem and achieve high accuracy control is certainly demanded.

Sliding mode control is a specific kind of nonlinear control [6], and it has been widely used in the industrial control field. Especially, sliding mode control has strong robustness to various disturbances, parameter perturbation and unmodeled dynamics. Aiming at this point, this article presents an active CG control method based on sliding mode control which provides the precise control performance and strong rejection ability to various disturbances.

This article is organized as follows. First, the overall scheme of active CG control system is presented in section Ⅱ. After that, modeling of CG varying with fuel transfer is described in section Ⅲ, and then the detailed design process of CG sliding mode control law is put forward in section Ⅳ. Then, simulations are carried out to verify the effectiveness of the proposed method. Finally, conclusions are stated.

II. DESIGN SCHEME OF ACTIVE CG CONTROL SYSTEM

With the continuous fuel consumption during flight, the aircraft's center of gravity position is always varying. Besides, some other factors, such as weapon launch, aircraft store separation, landing gear operation and loads movement, may also generate a direct effect on the aircraft CG position [7]. Especially for the supersonic aircraft, the aerodynamic center will obviously shift aft during transonic flight, leading to the unexpected increased distance between the aerodynamic center and CG. Consequently, the maneuvering ability and the cruise performance of the aircraft are dropped.

In order to solve the above problems, it is certainly demanded that the aircraft CG can be adjusted in flight to ensure the aircraft’s excellent performance. Then, the active CG control system based on fuel transfer is constructed, and its overall scheme is shown in Fig.1.

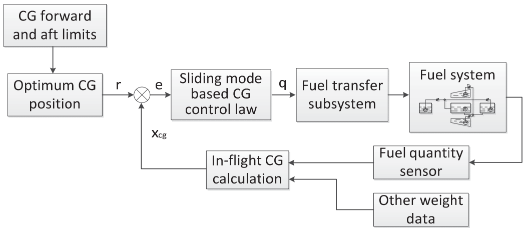

Fig.1. Overall scheme of active CG control system

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In this system, the longitudinal center of gravity position is adjusted by a fuel transfer system which changes the quality distribution of the fuel in forward and aft tanks. During different flight stages, the target CG position r can be obtained according to the CG optimization criteria to reduce the trim drag [1], simultaneously the real-time CG position x_{cg} is calculated based on the fuel quantity and other weight data of the aircraft. Then, on the basis of the command and the actual CG position, the deviation e can be obtained and transmitted to the center of gravity controller. The sliding mode based CG control law can generate the corresponding fuel flow rate signal, and enable the fuel transferred among fuselage tanks to achieve the new fuel distribution and eliminate the CG deviation.

III. MODELING OF CG VARYING WITH FUEL TRANSFER

The layout of all fuel tanks for a certain aircraft is shown in Fig.2. The fuel system consists of the forward fuel tank (tank 1 and tank 2), the central fuel tank (tank 3), the aft fuel tank (tank 4) and the wing tanks (tank 5). Among the tanks, the central tank 3 is mainly supplied fuel to the engines, and the other tanks are connected to each other by the corresponding fuel transfer lines.

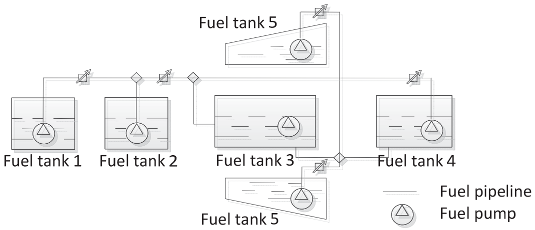

Fig.2. Layout of aircraft fuel tanks

According to the specific position and fuel weight of each tank, the longitudinal CG position of aircraft can be calculated as

$$x_{cg}(t) = \frac{M_0 x_{cg0} + \sum_{i=1}^{5} m_i \cdot x_{fi}}{M_0 + \sum_{i=1}^{5} M_i} \tag{1}$$

where $x_{cg}(t)$ refers to the longitudinal CG position. M_0, x_{cg0} are the zero fuel weight and the zero fuel CG position, respectively. $m_i, i = 1, \cdots, 5$ refers to the actual fuel weight of each tank. x_{fi} refers to the longitudinal position of each tank.

During the fuel transfer process, the fuel weight of each fuel tank m_i is continuously varying. Assuming that the fuel flow rate is q_i and the initial fuel weight is M_i, the fuel weight of each tank can be expressed as

$$m_i(t) = M_i + \int_{t_0}^{t} q_i(\tau) d\tau \quad i = 1, \cdots, 5 \tag{2}$$

where q_i is defined as positive when fuel flow into the tank.

Substituting (2) into (1) yields

$$x_{cg}(t) = \frac{M_0 x_{cg0} + \sum_{i=1}^{5} (M_i + \int_{t_0}^{t} q_i(\tau) d\tau) \cdot x_{fi}}{M_0 + \sum_{i=1}^{5} M_i} \tag{3}$$

Correspondingly, the initial longitudinal CG position is defined as

$$x_{cg}(t_0) = \frac{M_0 x_{cg0} + \sum_{i=1}^{5} M_i \cdot x_{fi}}{M_0 + \sum_{i=1}^{5} M_i} \tag{4}$$

Then the variation of aircraft CG due to fuel transfer can be obtained as

$$x_{cg}(t) = x_{cg}(t_0) + \frac{\sum_{i=1}^{5} x_{fi} \cdot \int_{t_0}^{t} q_i(\tau) d\tau}{M_0 + \sum_{i=1}^{5} M_i} \tag{5}$$

Computing the derivative of CG, we have

$$\dot{x}_{cg}(t) = \frac{\sum_{i=1}^{5} x_{fi} \cdot q_i}{M_0 + \sum_{i=1}^{5} M_i} \tag{6}$$

Equation (6) shows the relationship between CG and the fuel transfer rate. Based on this mathematical model, the CG control law can be designed to accurately adjust the longitudinal CG by fuel transfer.

IV. SLIDING MODE BASED CG CONTROL LAW

The general requirements for CG control law are high accuracy, high stability, and outstanding rejection ability to disturbances. For the control law design, disturbances from the flight attitude, fuel consumption and other system uncertainties are considered as a synthetic unknown disturbance. And then the sliding mode control law with strong disturbance rejection ability is designed to realize the precise and effective control of aircraft CG.

A. Design Process of Sliding Mode Control Law

The CG model (6) can be further described as a general form

$$\dot{x} = g(x) \cdot u \tag{7}$$

where $g(x)$ is the input matrix of the equation of state. And u is the input variables.

For this first-order system, the integral sliding mode surface can be designed as

$$s = k_1 \cdot e + k_2 \cdot \int e \cdot dt \tag{8}$$

where $e = r - x$ is the state error, and r refers to the target CG position.

The sliding mode reaching law is selected as

$$\dot{s} = -\varepsilon \cdot \mathrm{sgn}(s) - \lambda \cdot s \tag{9}$$

where $\varepsilon > 0$, $\lambda > 0$ are the positive gain.

Computing the derivative of (8), and substituting

$\dot{e} = \dot{r} - \dot{x} = \dot{r} - g(x) \cdot u$ into (8), (9) yields the sliding mode based CG control law as

$$u = g(x)^{-1} \cdot [\dot{r} + \frac{k_2}{k_1} \cdot e + \frac{\varepsilon}{k_1} \cdot \mathrm{sgn}(s) + \frac{\lambda}{k_1} \cdot s] \tag{10}$$

B. *Stability and Convergence Analysis*

In this section, the stability and convergence analysis of the CG control law (10) is carried out. The analysis process includes the approaching phase and the sliding mode phase.

First, a Lyapunov function is selected as

$$V = \frac{1}{2} s^2 \tag{11}$$

According to the expression of reaching law,

$$\dot{s} = -\varepsilon \cdot \mathrm{sgn}(s) - \lambda \cdot s \tag{12}$$

The derivative of (11) can be computed and obtained as

$$\begin{aligned} \dot{V} &= s \cdot \dot{s} \\ &= -\varepsilon \cdot s \cdot \mathrm{sgn}(s) - \lambda \cdot s^2 \\ &= -\varepsilon \cdot |s| - \lambda \cdot s^2 \end{aligned} \tag{13}$$

Obviously in the approaching phase, equation (13) meets

$$\dot{V} = -\varepsilon \cdot |s| - \lambda \cdot s^2 < 0 \tag{14}$$

According to the Lyapunov stability theory, the positive definite Lyapunov function $V = \frac{1}{2} s^2$ always meets $\dot{V} < 0$, then the control law can guarantee the phase trajectory beginning at any initial point will reach the sliding mode surface in finite time.

As the system state reaches the sliding surface, it is always satisfied $s = 0$. According to the expression of sliding mode surface, we have

$$s = k_1 \cdot e + k_2 \cdot \int e \cdot dt = 0 \tag{15}$$

Equation (15) can be solved as

$$e = C \cdot \exp(-\frac{k_2}{k_1} \cdot t) \tag{16}$$

where c is a constant which determined by error initial value e_0.

From (16) it can be concluded that the CG control error e can converge to zero.

As above, according to the Lyapunov stability theory and the characteristics of sliding mode surface, the sliding mode based CG control law

$$u = g(x)^{-1} \cdot [\dot{r} + \frac{k_2}{k_1} \cdot e + \frac{\varepsilon}{k_1} \cdot \mathrm{sgn}(s) + \frac{\lambda}{k_1} \cdot s]$$

can guarantee that the phase trajectory from any point reaches the sliding mode surface and the CG control error converges to zero in finite time.

V. SIMULATION AND ANALYSIS

In this paper, simulation analyses of the CG sliding mode control law are carried out under two different conditions, including fuel transfer between forward and aft tanks, fuel transfer among multiple tanks.

A. *Simulation analysis under the condition of fuel transfer between forward and aft tanks (SISO system)*

For the certain layout of aircraft fuel tanks shown in Fig.2, tank 2, tank 4 are set as the forward and aft fuel tanks respectively.

The initial fuel weight and location of each tank are set as $M_2 = 5000kg$, $x_{f2} = 16.66m$, $M_4 = 1500kg$, $x_{f4} = 28.79m$. The aircraft zero fuel weight and zero fuel CG position are set as $M_0 = 27546kg$, $x_{cg0} = 21.238m$. The mean aerodynamic chord is $c_A = 11.491m$, and the maximum fuel flow rate between the two tanks is assumed as $q = 7.182kg/s$.

In order to eliminate the chattering phenomenon of the sliding mode control law, the reaching law is improved as

$$\dot{s} = -\varepsilon \cdot \frac{s}{|s| + \delta} \tag{17}$$

where δ is a constant which satisfies $0 < \delta \leq 1$.

The parameters of the sliding mode based CG control law are selected as $k_1 = 1$, $k_2 = 100$, $\varepsilon = 0.15$, $\delta = 0.8$.

The control command is set as the sine signal as shown in Fig.3, and the corresponding CG response curve and the fuel transfer flow are shown in Fig.3 and Fig.4.

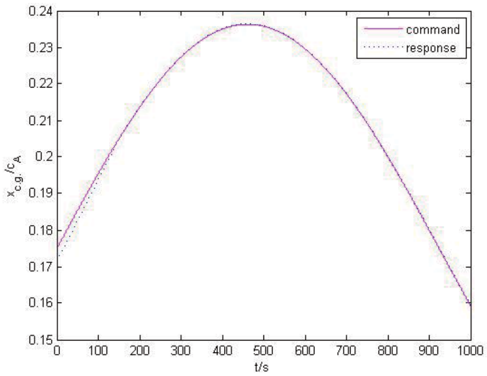

Fig.3. CG command and control response curves

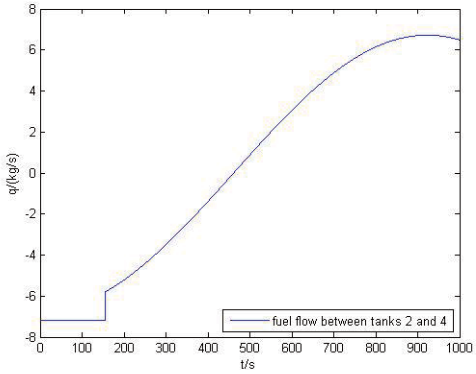

Fig.4. Fuel flow rate curve

As shown in Fig.3, CG response can precisely track the given command input which varies in the range of 16%c_A to 25%c_A, and the system has an excellent control performance. In the initial stage, there is a certain deviation between the initial CG position and the command. Due to the limit of the maximum fuel flow rate, the output response takes about 150s to track the given CG command. This is also verified by the fuel flow curve in Fig.4.

In the process of CG variation, the control signal of fuel flow rate achieves a steady change and eliminates the chattering phenomenon, satisfying the requirements of the CG control system.

In summary, for the forward and aft fuel transfer condition, CG can accurately and rapidly track the given command with the proposed sliding mode control law.

B. Simulation analysis under the condition of fuel transfer among multiple tanks (MISO system)

A further simulation analysis with multiple fuel tanks is carried out to verify the CG control law under a more complex condition.

The fuel tanks 1, 3, 4 and 5 in Fig.2 are selected for fuel transfer. The fuel flow rates between the forward tank 1 and the aft tanks 3, 4, 5 are q_1, q_2 and q_3, respectively, and the maximum fuel flow of each line is set as $q = 2.394kg/s$.

The initial fuel weights and locations of all tanks are set as $M_1 = 5600kg$, $x_{f1} = 12.53m$, $M_3 = 3000kg$, $x_{f3} = 25.03m$, $M_4 = 1500kg$, $x_{f4} = 28.79m$, $M_5 = 1000kg$, $x_{f5} = 25.38m$. The other parameters are the same as before.

The CG command is set as a slope signal and the parameters of sliding mode control law is selected as $k_1 = 1$, $k_2 = 50$, $\varepsilon = 0.05$, $\delta = 1$. The CG response and the fuel flow rate curves are shown in Fig. 5- Fig.8.

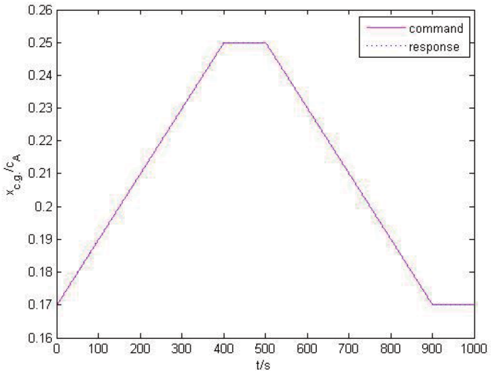

Fig.5. CG command and response curves

As shown in Fig.5, the CG command is shifted aft initially and then forward. In 0-400s, the CG command changes from 17%c_A to 25%c_A. Thereafter, the CG remains at the position 25%c_A until 500s. In 500-900s, the command changes from 25%c_A to 17%c_A, and then maintains to 1000s. The variation of CG command is accordance with the actual condition during flight.

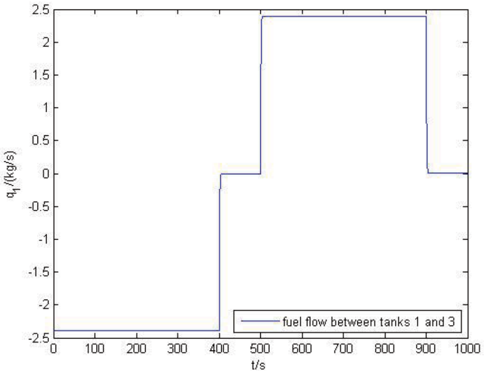

Fig.6. Fuel flow between tank 1 and tank 3

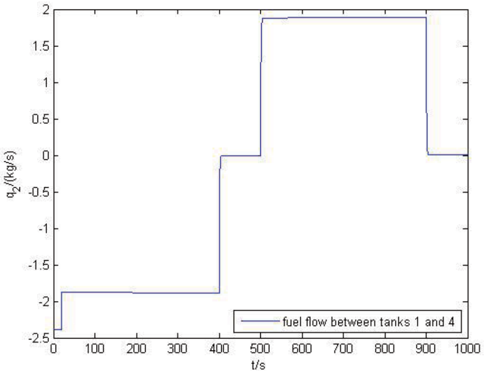

Fig.7. Fuel flow between tank 1 and tank 4

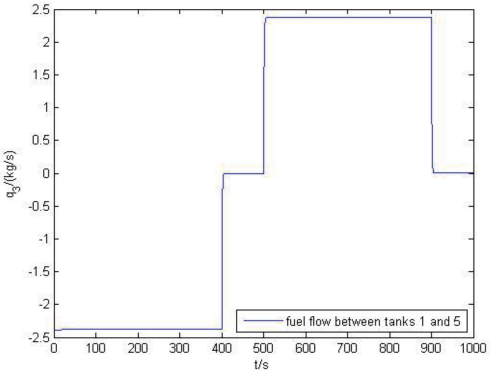

Fig.8. Fuel flow between tank 1 and tank 5

Fig.5 shows that, in the case of fuel transfer among multiple tanks, the CG response curve can also accurately track the given command. And in the whole process of CG shifting aft and forward, the sliding mode controller can provide excellent control performance. The fuel flow curves in Fig.6-Fig.8 indicate that the fuel transfer rates between the fuel tanks has not exceeded the maximum value, and there is no chattering phenomenon. In all, the proposed CG control law has excellent tracking performance under various fuel transfer conditions.

VI. CONCLUSION

As the basis of active center of gravity control for the advanced aircraft, modeling and CG control law are systematically investigated in this paper. The mathematic model of CG variation with fuel transfer is built. Then, a sliding mode based CG control law is presented to achieve the precise and effective control of aircraft CG. Simulation results demonstrate the effectiveness of the proposed method. A point to be taken into further consideration is deep analysis of the robust performance and disturbance rejection ability of this CG control law.

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