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# Aerodynamic model-based robust adaptive control for close formation flight

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A B S T R A C T

This paper presents an aerodynamic model-based robust adaptive control algorithm for close formation flight. The leader aircraft is assumed to be at level and straight flight which characterizes the most common scenario for close formation flight. The formation aerodynamic effects are assumed to be unknown, but an online formation aerodynamic model is available to predict those effects. In light of the online formation aerodynamic model, a robust adaptive control algorithm is thereafter developed on the follower aircraft to counteract the unknown formation aerodynamic effects and obtain highly accurate formation tracking performance. The proposed control algorithm is composed of a baseline controller and an integrator-augmented robust adaptive controller, which can efficiently deal with both matched and mismatched formation aerodynamic effects and external disturbances. The major advantage of the proposed design is that it can achieve at least ultimate bounded tracking control with certain transient performance guaranty. The efficiency and robustness of the proposed control design are eventually validated via numerical simulations of close formation flight at two different scenarios.



## 1. Introduction

Close formation flight problem has received extensive research attention in the past decades, owing to its potential in energy saving [1–3]. In close formation flight, a follower aircraft is required to fly at relatively close separation to a leader aircraft. The upwash wake of the trailing vortices induced by the leader aircraft could, therefore, be efficiently utilized by the follower aircraft to reduce its drag and fuel consumption. The potentials of close formation flight in drag reduction and fuel saving have been investigated and validated from different perspectives, such as analytical analysis [4–6], simulation verifications [7], wind tunnel experiments [8], and real flight tests [9,10] etc. Those research works also indicate that highly accurate and robust control algorithm is indispensable for successful implementation of close formation flight. As shown in [6], more than 30% of the formation aerodynamic benefits will be lost, if the optimal relative position cannot be tracked and maintained within at least 10% wing span by the follower aircraft.

So far, the robust close formation control problem has been investigated in terms of many methods with different considerations. In [11], a proportional-integral (PI) formation-holding controller is developed to allow the follower aircraft in close formation to robustly hold its optimal position under the influence of formation aerodynamic forces. The follower is assumed to be initially well-trimmed at its optimal position in close formation. The formation aerodynamic forces were addressed in terms of their gradient information. Instead of directly addressing the aerodynamic force disturbances, the PI controller is designed to be only robust to perturbations in these disturbances as the follower deviates from its optimal position. The PI formation-holding controller is thereafter modified by Kumar et al. [12] and Shan et al. [13] using an adaptive-random-search approach and a motion synchronization strategy, respectively. To avert the usage of aerodynamic force gradients, a linear model predictive control (MPC) algorithm was proposed in [14]. However, the formation aerodynamic forces are assumed to be constant to ensure the feasibility of the MPC law. In [15], Singh et al. developed a sliding model controller for robust formation tracking control. The vortex force-related matrices must be available and satisfy certain boundary requirements to guarantee the stability. The time derivative of the lift is chosen as one of the control inputs, which makes their design less practical. A more practical robust formation tracking control method was proposed by the authors in [16], in which the formation aerodynamic forces are counteracted by an uncertainty and disturbance estimator (UDE). Once again, only formation aerodynamic forces are considered in the robust design. The robust formation-holding control with the consideration of both formation aerodynamic

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forces and moments was investigated by using LQR technique [17]. The close formation control problem has also been investigated using other methods, including the extremum-seeking algorithm [18,19], quasi-continuous high order sliding mode control (HOSM) [20], and neural network-based adaptive control [21,22], etc.

However, most of the current efforts focus on the close formation-holding control, but more complex formation tracking control hasn't received much research attention. Even for the formation-holding design, formation aerodynamic effects are all assumed to be matched with control inputs, though some of the effects are surely mismatched with control inputs. The transient performance due to the initial formation position errors fails to be considered and guaranteed to any extent by all current designs, though it is of great importance for the formation flight in such close separations. Despite different models have been proposed to describe the aerodynamics of close formation flight, they haven't been used online by any methods to improve the control performance.

In this paper, a novel aerodynamic model-based robust adaptive control is proposed for highly accurate and robust close formation flight. The leader aircraft is assumed to be at level and straight flight. An online aerodynamic model is employed to predict the formation aerodynamic effects. The unknown matched and mismatched formation aerodynamic effects will be counteracted by an integrator-augmented robust adaptive controller using predictions from an online aerodynamic model. The proposed control algorithm will be implemented on the follower aircraft to steer it to its optimal position in close formation, and robustly maintain that position under unknown formation aerodynamic effects and external disturbances. It is well accepted that robust control is placed in handling disturbances and uncertainties. Many existing robust control designs—often based on worst-case scenarios—may lead to high-gain control. Such a design is not desirable, due to implementation concerns and actuation constraints. On the other hand, a robust adaptive controller can potentially handle disturbances or uncertainties in an online-adjustment fashion that makes the design more efficient and applicable. Therefore, it is the topic of interest presented in this paper to study its design in addressing aerodynamic disturbances in close formation. In comparison with the robust design merely in light of integral control, the proposed adaptive control can also guarantee some transient performance and ultimate boundedness. The proposed robust adaptive design is established based on a valid aerodynamic model instead of neural networks, which makes it more reliable and efficient. In addition, this paper focuses more on the control design for close formation flight. For other interesting topics in formation control, readers are suggested to read the papers [23–25] and the references therein.

The rest of this paper is organized as follows. In Section 2, the major problem is formulated and a linear close formation model is introduced. Section 3 presents an online formation aerodynamic model. The aerodynamic model-based robust adaptive close formation controller is described in Section 4, while the control performance will be analyzed in Section 5. Finally, numerical simulations are given in Section 6, and the conclusion remarks are summarized in Section 5.

## 2. Problem formulation

During close formation flight, leader aircraft is assumed to be at level and straight flight. The follower aircraft is required to track and maintain a certain optimal relative position to the leader aircraft. The proposed close formation controller will be established in light of the leader–follower architecture, and be eventually implemented to the follower aircraft. Without loss of generality, follower aircraft is also assumed to be at level and straight flight at

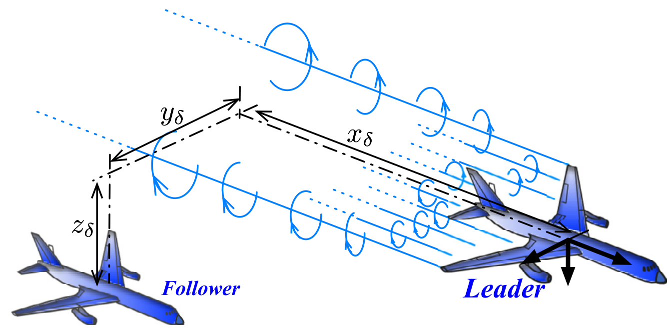


**Fig. 1.** Close formation flight.

the beginning of any flight maneuvers to achieve the final close formation. Based on the small perturbation assumption, close formation dynamics will be characterized in terms of a linearized decoupled 6-DOF aircraft model as shown below.

$$\left.\begin{aligned}
\dot{V}_\delta &= -\frac{D_V}{m}V_\delta - g\theta_\delta + \left(g - \frac{D_\alpha}{m}\right)\alpha_\delta + \frac{T_{max}\cos\alpha_0}{m}\delta_T + \frac{\Delta D}{m}\\
\dot{\theta}_\delta &= q\\
\dot{\alpha}_\delta &= q - \frac{T_0\cos\alpha_0 + L_\alpha}{mV_0}\alpha_a - \frac{\Delta L}{m(V_0+V_\delta)}\\
\dot{q} &= c_1\mathcal{M}_q q + c_1\mathcal{M}_\alpha\alpha_\delta + c_1\mathcal{M}_{\delta_e}\delta_e + c_1\Delta\mathcal{M}\\
\dot{x}_\delta &= V_\delta\\
\dot{z}_\delta &= V_0\alpha_\delta - V_0\theta_\delta
\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}
\dot{\phi}_\delta &= p\\
\dot{\psi}_\delta &= r\\
\dot{\beta}_\delta &= \sin\alpha_0 p - \cos\alpha_0 r - \frac{T_0\cos\alpha_0 - Y_\beta}{mV_0}\beta_\delta + \frac{\Delta Y}{m(V_0+V_\delta)}\\
\dot{p} &= \left(c_2\mathcal{L}_\beta + c_3\mathcal{N}_\beta\right)\beta_\delta + \left(c_2\mathcal{L}_p + c_3\mathcal{N}_p\right)p + \left(c_2\mathcal{L}_r + c_3\mathcal{N}_r\right)r\\
&\quad + \left(c_2\mathcal{L}_{\delta_a} + c_3\mathcal{N}_{\delta_a}\right)\delta_a + \left(c_2\mathcal{L}_{\delta_r} + c_3\mathcal{N}_{\delta_r}\right)\delta_r + c_2\Delta\mathcal{L}\\
&\quad + c_3\Delta\mathcal{N}\\
\dot{r} &= \left(c_3\mathcal{L}_\beta + c_4\mathcal{N}_\beta\right)\beta_\delta + \left(c_3\mathcal{L}_p + c_4\mathcal{N}_p\right)p + \left(c_3\mathcal{L}_r + c_4\mathcal{N}_r\right)r\\
&\quad + \left(c_3\mathcal{L}_{\delta_a} + c_4\mathcal{N}_{\delta_a}\right)\delta_a + \left(c_3\mathcal{L}_{\delta_r} + c_4\mathcal{N}_{\delta_r}\right)\delta_r + c_3\Delta\mathcal{L}\\
&\quad + c_4\Delta\mathcal{N}\\
\dot{y}_\delta &= V_0\beta_\delta - V_0\sin\alpha_0\phi_\delta + V_0\sin\alpha_0\sin\theta_0\psi_\delta
\end{aligned}\right\} \quad (2)$$

where $x_\delta$, $y_\delta$, and $z_\delta$ denote the relative position of the follower aircraft to its leader in the wind frame of the leader aircraft as shown in Fig. 1, $V_\delta$, $\phi_\delta$, $\theta_\delta$, $\psi_\delta$, $\alpha_\delta$, and $\beta_\delta$ specify relative states of the follower aircraft to its leader in close formation, $p$, $q$, and $r$ are angular rates of the follower aircraft, $c_1 = \frac{1}{I_y}$, $c_2 = \frac{I_z}{I_xI_z - I_{xz}^2}$, $c_3 = \frac{I_{xz}}{I_xI_z - I_{xz}^2}$, and $c_4 = \frac{I_x}{I_xI_z - I_{xz}^2}$, where $I_x$, $I_y$, $I_z$, and $I_{xz}$ are moments of inertia, $D_V$ and $D_\alpha$ are drag derivatives, $L_\alpha$ is the lift derivative, $Y_\beta$ is the side force derivative, $\mathcal{L}_\beta$, $\mathcal{L}_p$, $\mathcal{L}_r$, $\mathcal{L}_{\delta_a}$, and $\mathcal{L}_{\delta_r}$ represent the rolling moment derivatives, $\mathcal{M}_q$ $\mathcal{M}_\alpha$, and $\mathcal{M}_{\delta_e}$ are the pitching moment derivatives, $\mathcal{N}_\beta$ $\mathcal{N}_p$, $\mathcal{N}_r$, $\mathcal{N}_{\delta_a}$, and $\mathcal{N}_{\delta_r}$ denote the yawing moment derivatives, $T_{max}$ specifies the maximal thrust of the follower aircraft, $m$ is the mass of the follower aircraft, $g$ denotes the gravity acceleration, $V_0$, $\alpha_0$, $\theta_0$ and $T_0$ characterize the trimming conditions for the follower aircraft, and the leader aircraft of the same size is assumed to have the same trimming conditions at level and straight flight, $\Delta D$, $\Delta L$, and $\Delta Y$ are vortex-induced incremental forces on the follower aircraft in close formation, and $\Delta\mathcal{L}$, $\Delta\mathcal{M}$, and $\Delta\mathcal{N}$ denote the vortex-induced incremental moments on the follower aircraft.

Notice that the effects of $\Delta D$, $\Delta\mathcal{L}$, $\Delta\mathcal{M}$, and $\Delta\mathcal{N}$ can be represented in the same channels with control surfaces, but that the effects of $\Delta L$ and $\Delta Y$ fail to be converted directly into the same