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Dynamic and control issues of formation flight

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Abstract

Two aspects of formation flight are addressed in this paper: dynamic modeling and formation control. In formation flight aircraft dynamics are coupled by aerodynamic effects due to the vortices leaving the lifting surfaces, such as changes in lift and drag forces and lateral/directional effects that do not appear in a steady-level 'isolated' flight. These aerodynamic effects are properly modeled with a three dimensional code based on a Distributed Horse-Shoe Technique. A formation controller allowing both trajectory tracking and formation geometry keeping is then designed. It is shown that the designed controller yields satisfactory performance in a two-aircraft formation.

Keywords: Formation flight; Horse-shoe vortex; Trajectory tracking; Migrational birds; LMI design

1. Introduction

The growing employment of Unmanned Air Vehicles (UAVs) has highlighted the power of such systems for surveillance, reconnaissance and rescue tasks in both military and civil applications.

The operational potential of UAVs could strongly be improved by making them flying within a close formation. The first advantage of this kind of arrangement comes from aerodynamic effects. Indeed it is well known that aircraft with large aspect ratio wings have better overall aerodynamic efficiency because of reduction in drag for a given lift. However, large aspect ratio implies large wingspan for a given area, this means that the resulting structure will be unreasonably flexible and fragile for lightweight design. A similar improvement in global efficiency can be achieved by flying multiple aircraft in close formation where the aerodynamic benefits are due to favorable wake-vortex encounters. In fact, the up-wash components of the vortex system leaving the trailing edge of each surface reduce the downward velocities induced by the aircraft's own trail and hence its induced drag. Because of the reduction in drag, less power is required to maintain the desired forward velocity and thus each aircraft of a formation has a better performance than when flying singly. Moreover, from an operational point of view, many aircraft involved in a mission can be better managed if they fly in a formation, rather than in an undefined structure. Since the first study by Wieselsberger, [15], the mathematical modeling of the aerodynamic interference between different aircraft in a formation is object of study among researchers for different purposes. Hummel investigated on aerodynamics aspects of birds formation flight, [11, 13], while Bloy and co-workers considered the problem of aerodynamic interference on lateral directional stability during air-to-air refuelling maneuvers, [3,4].

Close formation flight control, intended as a guidance, navigation and control problem, was originally studied for a classic Leader/Wingman configuration.

An aircraft (Leader) is selected to direct the formation, following a prescribed path, and all the other airplanes (Wingmen) are expected to maintain a fixed relative distance with respect to the lead airplane, in order for the formation to maintain a desired geometrical shape. In Refs. [2,

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12], Beukenberg and Hummel describe an autopilot for formation flight where the Wingman aircraft has to maintain the maximum power reduction position. Later, D'Azzo and co-workers analyzed the kinematic coupling effect of the two-aircraft Leader/Wingman configuration, and introduced a proportional integral (PI) controller for formation control [6].

In Ref. [9], two different Leader/Wingman structures were developed. In Leader-Mode, each Wingman takes the trajectory reference from the Leader of formation while in Front-Mode each aircraft takes its reference from the preceding one.

The rest of the present paper is organized as follows. Section 2 describes the formation modeling. Variations in forces and moments coefficients due to aerodynamic interference, and kinematic equations of the relative distance between aircraft are presented.

Section 3 presents a new approach to formation flight. In the proposed strategy, each aircraft does not refer to the preceding one or to the formation leader, but keeps its position with respect to an imaginary point in the formation whose dynamics depend on all the aircraft positions. The approach is based on the apparent behavior of some migrational birds, that during a migrational flight 'wait' for those birds which have changed the original geometry of the formation by flying in a different path. The formation controller is constituted by two components: a trajectory controller, which provides tracking of a prescribed path, and a position controller which permits formation geometry keeping. These control laws are mixed by a parameter that depends on the position error. Simulations showing the application of the outlined control laws are presented, including a comparison between the classical Leader/Wingman structure and the proposed strategy.

2. Formation dynamics

The first, important challenge in the study of formation flight is represented by the complexity of the aerodynamic coupling. Aerodynamic interference between different aircraft in the formation needs to be fully evaluated, modeled and quantified since it may have critical effects. While the increase in lift and drag reduction improve the aerodynamic efficiency, additional rolling and yawing moments are generated, since the aerodynamic induction is not symmetrical. This may cause critical effects on the handling qualities and thus the control system designed for an isolated flight condition could be inadequate, leading the system to closed loop unstable conditions.

For the purposes of the present effort an approach to aerodynamic modeling, based on the distributed Horse-Shoe Vortex Theory is used.

Such technique allows to estimate variations in aerodynamic coefficients for each aircraft within the formation with respect to the 'isolated' flight. Details can be found in the literature, [2,7].

Aerodynamic coefficients vector is now made of two different contributions:

$$\begin{pmatrix} \boldsymbol{C}_F \\ \boldsymbol{C}_M \end{pmatrix} = \begin{pmatrix} \boldsymbol{C}_F{}^{(i)} \\ \boldsymbol{C}_M{}^{(i)} \end{pmatrix} + \begin{pmatrix} \boldsymbol{\Delta} C_F \\ \boldsymbol{\Delta} C_M \end{pmatrix}. \tag{1}$$

The first term of the right hand side of the previous equation contains the aerodynamic coefficient in case of 'isolated' flight, while the second is related to the contributions associated by formation flying. Clearly, the terms $\boldsymbol{\Delta} C_F$ and $\boldsymbol{\Delta} C_M$, are function of the relative distances between the aircraft.

By using polynomial functions to describe aerodynamic coefficients and referring to the aerodynamic frame $\mathbb{F}_a$, according to Eq. (1) one has:

$$\begin{aligned}
C_D &= C_{D_0} + C_{D_\alpha}\alpha + C_{D_q}\frac{q\bar{c}}{V_a} + C_{D_{\delta_e}}\delta_e + \boldsymbol{\Delta C_D},\\
C_Y &= C_{Y_0} + C_{Y_\beta}\beta + C_{Y_p}\frac{pb}{V_a} + C_{Y_r}\frac{rb}{V_a} + C_{Y_{\delta_a}}\delta_a\\
&\quad + C_{Y_{\delta_r}}\delta_r + \boldsymbol{\Delta C_Y},\\
C_L &= C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}\frac{q\bar{c}}{V_a} + C_{L_{\delta_e}}\delta_e\\
&\quad + C_{L_{\dot\alpha}}\dot\alpha + \boldsymbol{\Delta C_L}
\end{aligned} \tag{2}$$

and

$$\begin{aligned}
C_l &= C_{l_0} + C_{l_\beta}\beta + C_{l_p}\frac{pb}{V_a} + C_{l_r}\frac{rb}{V_a} + C_{l_{\delta_a}}\delta_a\\
&\quad + C_{l_{\delta_r}}\delta_r + \boldsymbol{\Delta C_l},\\
C_m &= C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}\frac{q\bar{c}}{V_a} + C_{m_{\delta_e}}\delta_e\\
&\quad + C_{m_{\dot\alpha}}\dot\alpha + \boldsymbol{\Delta C_m},\\
C_n &= C_{n_0} + C_{n_\beta}\beta + C_{n_p}\frac{pb}{V_a} + C_{n_r}\frac{rb}{V_a} + C_{n_{\delta_a}}\delta_a\\
&\quad + C_{n_{\delta_r}}\delta_r + \boldsymbol{\Delta C_n}.
\end{aligned} \tag{3}$$

2.1. Formation kinematics

To maintain the formation geometry, each aircraft must keep its prescribed distance from a reference. To calculate the relative distance of the ith aircraft from its reference r, three reference frames are introduced: an inertial, Earth-fixed frame $\mathbb{F}_O$ and two wind axis frames $\mathbb{F}_{k_i}$ and $\mathbb{F}_{k_r}$, with the origin on the CG of the ith aircraft and on its reference r respectively.

The relative distances between the ith aircraft and its reference r is computed first referred to the inertial frame and then rotated to the kinematic frame. The distance between the ith aircraft from its reference r, referred to the inertial frame is defined as

$$\mathbf{d}_i^O = \mathbf{P}_r - \mathbf{P}_i, \tag{4}$$

where $\mathbf{P}_i$ and $\mathbf{P}_r$ are the position of the ith aircraft and its reference in the Earth-fixed frame $\mathbb{F}_O$. Then, the distance of