Research Article

Numerical Aerodynamic Characteristics Analysis of the Close Formation Flight

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1. Introduction

Multiple UAV formation flight shows significant promise to a single UAV in the ability to adapt to complex environmental conditions and the efficiency of task execution through cooperative UAV operations [1, 2], so the formation flight of multiple UAV has attracted the interest of researchers all over the world. One of the most important researches on the formation flight is the aerodynamic interference effect between UAVs, particularly in close formation flight. Numerous researches show that aircraft flying in close formation have many advantages in energy saving and fuel efficiency by surfing the wingtip vortex of the aircraft ahead of them, and this results in an increase in the range capability of each aircraft in the formation. Therefore, it is a meaningful research subject to analyze the aerodynamic characteristics of the close formation flight and design reasonable formations for UAVs based on the favorable aerodynamic interference effect between UAVs.

The research of aircraft formation flight is inspired by the formation flight of birds. It is well known that birds flying in the V formation during migration are able to increase their range and endurance. In 1914, Wieselsberger first investigated the formation flight through aerodynamic theoretical approach by using a simple aerodynamic model and concluded that the V formation would be desirable for approximate equipartition of drag [3]. In 1970, Lissaman and Shollenberger found that a formation of 25 birds could have a range increase of 71 percent as compared with a single bird [4]. Through photographic study of Canadian Geese in 1987, Hainsworth indicated that the lateral spacing between adjacent birds was very close to the optimum predicted by the simple aerodynamic theory [5]. In 2001, Weimerskirch and Martin confirmed that pelicans exhibited reduced heart rate while flying in formation, providing further evidence of formation flight benefits [6].

Inspired by migratory bird species fly in closely spaced flocks, researchers have done a lot of work to investigate
how aircraft can fly in formation and obtain improvement in aerodynamic performance. Hummel represented aircraft with single horseshoe vortexes to achieve power reductions by making use of aircraft wakes in the close formation flight [7], and Wagner investigated drag reduction and interference effects in tight formation flight by using vortex lattice codes [8]. Wang and Mook adopted a general unsteady vortex lattice method to analyze the aerodynamics of formation flight; the results showed that there could be an increase in lift as well as an unbalanced roll moment for formation flights, and the lift increased due to the vortex interference was associated with a reduction in the induced drag [9]. Gingras performed wind tunnel tests to investigate a multi-aircraft formation. They verified that the wind tunnel test methods were accurate enough to be used for control law design of automated systems [10]. Blake compared the results of vortex lattice method and wind tunnel test for two delta wings in close proximity; a maximum induced drag reduction of 25% was measured on the trail aircraft by wind tunnel test, compared with a 40% predicted reduction using the vortex lattice method; the results also showed that the wake effects on lift were slightly overpredicted by the vortex lattice method, while the wake induced effects on pitching and rolling moment were well predicted [11].

A large number of flight tests have also been used to confirm the aerodynamic benefit associated with flying in formation. Beukenberg and Hummel used two Dornier Do-28 aircraft for flight tests and found that about 15% of maximum flight power reductions could be realized for practical flight [12]. The most serious flight test program to date was the Autonomous Formation Flight project, which was funded by NASA as part of its Revolutionary Concepts Program. The date of flight test indicated that a 15-20% reduction in drag had been achieved for the trailing F/A-18 aircraft [13–15]. In 2008, DARPA and the Air Force Research Laboratories began to fund the Formation Flight for Aerodynamic Benefit program to verify the ability of the C-17s by flying in formation; it was demonstrated that greater than 10% fuel burn savings for the trailing aircraft could be autonomously achieved over long durations [16, 17]. Then, the Air Force Research Lab investigated the possibility of using formation flight in coronet missions to save fuel through operational analysis; the results showed that a 14.15% and a 14.53% reduction in thrust were possible for the F-15C and F-15E, respectively [18, 19].

With the rapid development of technology in sensing and control, the instruments to track the wake vortex and the automatic control systems to keep close formation flight are well designed, so the promising concept of improving the aerodynamic performance of UAVs by flying in close formation can be realized in the near future. However, most of the existing literature related to close formation flight are limited to general manned aircraft; few attention has been paid to close formation flight for UAVs. Thus, this paper will investigate the aerodynamic benefits of formation flight for two tailless delta wing UAVs and then discuss several different formations for three UAVs. It is expected that the research of this paper can technically support the application of close formation flight for UAVs.

2. Numerical Method

2.1. Governing Equations. All numerical simulations are performed with the finite volume solver (CFX-15.0) to solve three-dimensional Navier-Stokes (N-S) equations. The N-S equations represent the principles of mass and momentum conservation for a fluid in motion and can be written as follows [20]:

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} + S_u \tag{1}
\]

\[
\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho u v) = \nabla \cdot (\mu \nabla v) - \frac{\partial p}{\partial y} + S_v \tag{2}
\]

\[
\frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho u w) = \nabla \cdot (\mu \nabla w) - \frac{\partial p}{\partial z} + S_w \tag{3}
\]

where \(\rho\) is the fluid density, \(t\) is time, \(u\) is velocity vector, \(v\), \(w\), and \(w\) are components of \(u\) on \(x\), \(y\), and \(z\) axes, \(p\) is pressure on the fluid microelement, \(\nabla \cdot \) is the divergence, \(\nabla / \) is the gradient, and \(S_u\), \(S_v\), and \(S_w\) are the generalized source term of momentum conservation equations on directions \(u\), \(v\), and \(w\).

The N-S equations are complex, coupled, and nonlinear and thus insoluble analytically for anything but the simplest cases. For turbulent flows, the Reynolds Averaging technique is used to decompose the instantaneous flow variables into their average values and turbulent fluctuations, while the Boussinesq eddy-viscosity hypothesis is used to relate the Reynolds stress tensor and turbulent heat flux terms to the average flow variables.

The turbulence model of the flow field applies the standard \(k-e\) equations [21]:

\[
\frac{\partial (pk)}{\partial t} + \frac{\partial (pk u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b \tag{4}
\]

\[
- \rho e - Y_M + S_k
\]

\[
\frac{\partial (pe)}{\partial t} + \frac{\partial (p e u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_e} \right) \frac{\partial e}{\partial x_j} \right] + C_1 k \frac{\varepsilon}{k} \left( G_k + C_{3k} G_b \right) \tag{5}
\]

\[
- C_2 \rho k \varepsilon^2 \frac{\varepsilon}{k} + S_{\varepsilon}
\]

where \(k\) is turbulent kinetic energy, \(\varepsilon\) is the turbulent dissipation rate, \(u_i\) is the time average velocity, \(\mu\) is kinematic viscosity of the fluid, \(\mu_t\) is dynamic viscosity, \(\sigma_k\) and \(\sigma_e\) are Prandtl constant with turbulent kinetic energy \(k\) and turbulent dissipation rate \(\varepsilon\), \(G_k\) is the production of turbulent kinetic energy \(k\) due to average velocity gradient, \(G_e\) is the production of turbulent kinetic energy \(k\) caused by buoyancy, \(Y_M\) is the contribution of pulsating dilatation in compressible turbulence, \(C_{1k}, C_{2k}\), and \(C_{3k}\) are empirical constants, and \(S_k\) and \(S_{\varepsilon}\) are the source terms defined by the user.
A system with heat exchange flow should meet energy conservation equation as follows:

\[
\frac{\partial (\rho T)}{\partial t} + \text{div} (\rho u T) = \text{div} \left( \frac{k}{\epsilon_p} \text{grad} T \right) + S_T \tag{6}
\]

where \( T \) is Kelvin’s temperature (K); \( k \), is heat transfer coefficient; \( \epsilon_p \) is specific heat capacity; \( S_T \) is viscous dissipation item.

2.2. Geometry and Mesh. The numerical simulations are performed using Computational Fluid Dynamics (CFD), and the UAV used for aerodynamic analysis of close formation flight is a simplified tailless delta wing configuration (see Figure 1). The main dimensions of the UAV are as follows: length: 10 m, height: 1.7 m, wingspan: 10.9 m, leading edge sweep angle: 60 degree, and mean aerodynamic chord: 4.2 m.

In the analysis of close formation flight for two UAVs, the UAV flying ahead is called “leading UAV”, and the other one is the “trailing UAV”. Figure 2 shows the relative position of the two UAVs. The X-direction distance (lateral spacing), Y-direction distance (longitudinal spacing), and Z-direction distance (vertical spacing) between the UAVs are defined based on the nose-to-nose distance of the two UAVs.

The procedures of the numerical aerodynamic analysis for formation flight are arranged as follows. At first, the aerodynamic characteristics of a single UAV are calculated. The result of a single UAV can be used as the reference to the variation of aerodynamic values in the comparison with close formation flight. Then, the vortex effects of the leading UAV on the aerodynamic characteristics of the trailing UAV in the two UAV close formation flight are analyzed. The position where the trailing UAV obtains the maximum lift-to-drag ratio is defined as the optimal position, where the trailing UAV can obtain the largest aerodynamic improvement. Finally, three different types of three UAV formations are designed based on the optimal position to explore the preliminary application of the aerodynamic benefits in close formation flight for multiple UAVs.

The models are meshed in the software ANSYS ICEM CFD and all the grids are generated based on the unstructured tetrahedral mesh. In order to improve the accuracy of simulation, especially to capture the wingtip vortex of UAVs, 15 boundary layer meshes are used based on the surface of the UAVs and the meshes near the wingtip vortex in the flow field are refined. The total mesh number is 11,250,000. Figure 3 shows the distributions of surface meshes, near-wall meshes, and densified region near the wingtip vortex of the simulation model.

The initial conditions of the close formation flow field are set as follows: (1) the altitude of close formation flight is 10 km, the corresponding atmospheric density is 0.4135 kg/m³, the pressure is 26500 Pa, the temperature is 223.3 K, and the dynamic viscosity is 1.6282 × 10⁻⁵ N · s/m²; (2) the inlet velocity of airflow field is 0.7 Ma; (3) the outlet flow is free outlet.

2.3. Verification of the Numerical Simulation. In order to validate the accuracy of the simulation approach, the numerically obtained aerodynamic forces and moments of the CT-1 model are compared to the experimental data from wind tunnel test. The CT-1 model is a standard model provided by the China Aerodynamics Research and Development Center to verify the accuracy of CFD software [22]. Figure 4 shows the comparison of the calculation results and the experimental data. It can be seen that the calculated values agree well with the experimental data, except at the high angles of attack, which validates the accuracy of the computational method in this paper. Figure 5 shows the pressure contours of the CT-1 model at 35 degrees of attack. It can be seen that the strake vortex and leading edge vortex of the CT-1 model can be captured clearly. In addition, all the calculation models in this paper are set at small angles of attack, so the CFD has high accuracy to ensure the credibility of the calculation. Therefore, the numerical approach is reliable to investigate the tanker wake effects on the trailing UAV in this study.

3. Aerodynamic Analysis of the Close Formation Flight for Two UAVs

Munk’s stagger theorem suggests that longitudinal distance brings less variation to effect on the aerodynamic characteristics in close formation flight [23], so this section mainly discusses the effect of lateral and vertical distance on the aerodynamic characteristics of the trailing UAV.

Two identical simplified tailless delta wing UAVs are used in this research to investigate the effect of the leading UAV’s wingtip vortex on the trailing UAV in the close formation flight. Both the angles of attack with the UAVs are set up to 3 degrees. The numerical calculation arrangement is shown in Figure 6, the trailing UAV is located at 2b behind the leading aircraft in the longitudinal direction, and the lateral spacing between two UAVs is changed from 0.5b to 1.25b with the interval of 0.125b and the vertical spacing is changed from -0.25b to 0.25b with the interval of 0.125b, where b represents the wing span of UAV.

At first, the aerodynamic characteristics of a single UAV are measured. The result of a single UAV can be used as the reference in the variation of aerodynamic values. Figures 7 and 8 show the velocity contours and the streamlines at the longitudinal cross section (x/b = 2). It can be seen that there is strong upwash flow near the wingtip of the single UAV, and the downwash area of the flow field behind the single UAV is mainly concentrated at about -0.85b~0.85b lateral spacing.
Figure 9 shows the result of the effect of the leading UAV’s wingtip vortex on the trailing UAV in the close formation flight; it will be explained and discussed in incremental form.

The trialing UAV starts at the same height with the leading UAV and moves laterally toward to the right of the leading UAV. As shown in Figure 9(a), the vortex effect on the trailing UAV produces an increasing incremental lift coefficient as the trailing UAV moves inboard. When the lateral spacing approaches about 0.875b, the increment of lift coefficients reaches the maximum. The incremental lift coefficients change slope and diminish as the lateral spacing further decreases. At about 0.55b of lateral spacing the vortex produces a negative effect on the lift coefficients of the trailing UAV and the negative effect increases as the trailing UAV moves more inboard. The effect of the vertical spacing on the close formation flight can also be clearly seen from the calculation results, the change trend of the incremental lift coefficients is almost the same at different vertical height, but overall, the effect of the wingtip vortex on the trailing UAV decreases as the vertical distance between the UAVs increases.

Figures 10 and 11 show the pressure contours on the upper surface and lower surface of the two UAVs in the close formation, with a 0.5b lateral spacing at the same height. It can be clearly seen that the pressure on the leading edge of left wing for the trailing UAV is significantly lower than that of right wing; this is because the left wing is under the upwash flow of the leading UAV’s wingtip vortex, while the right wing is under the downwash flow. The leading edge pressure distribution has a dominant effect on the lift of the wing, the higher leading edge pressure leads to a lower lift, and
Figure 4: The comparison of the calculation results and the experimental data.

Figure 5: The pressure contours of the CT-1 model.
the lower leading edge pressure corresponds to a higher lift. Therefore, the lift of the right wing of trailing UAV decreases while the lift of the left wing increases. The decrement of the right wing's lift is higher than the incremental lift of the left wing, so the overall lift of the trailing UAV decreases under the calculated formation flight position.

Figures 12 and 13 show the upper surface pressure contour and velocity streamlines of the two UAVs in the close formation at 0.875b lateral spacing. Due to the upwash effect of the leading UAV’s wingtip vortex, the pressures on the upper surface of the left wing and right wing for the trailing UAV are significantly reduced, thus leading to the maximum lift coefficient of the trailing UAV.

The results of the vortex effect on the drag coefficient of the trailing UAV are shown in Figure 9(b). Firstly, the close formation of the two UAVs at the same height is analyzed; the black line with black spots reflects the effect of the lateral spacing on the drag coefficient of the trailing UAV. Out of the wingtip of the leading UAV, the drag coefficient of the trailing UAV in the close formation is only a small decrease compared with that of a single flight. Once the wingtip overlaps as the trailing UAV moves inboard in the lateral direction, the drag coefficient decreases sharply and then tends to stability at about 0.5b~0.75b lateral spacing. From the vertical direction, we can see that the wingtip vortex effect on the drag coefficient of the trailing UAV decreases as the vertical distance between the UAVs increases.

The results can be clearly explained by the flow field structure of the close formation flight; Figure 14 shows the vortex
Figure 9: Incremental coefficients of the aerodynamic forces and moments for the trailing UAV.
core region of the two UAVs with 0.75b lateral spacing at the same height; the vortex core region is rendered by swirling strength, which represents the imaginary part of complex eigenvalues of velocity gradient tensor. It is positive if and only if the discriminant is positive and its value represents the strength of swirling motion around local centers. In this figure, the level of the swirling strength is 0.001, and the actual value is 6.56/s. Figure 15 shows the vorticity contour of the two UAVs at the cross section (y/b = 0.95). It can be seen from the figure that the right wingtip vortex of the trailing UAV is strongly disturbed by the left wingtip vortex of the leading UAV; thus the downwash induced by the wingtip vortex of trailing UAV is intensively suppressed by the upwash of the leading UAV. As the classical view of aerodynamics, most of the induced drag for the aircraft in subsonic flight is derived from the downwash of the wingtip vortex. Therefore, the drag coefficients of the trailing UAV decrease due to the downwash reduction. It can also be seen from the velocity streamlines of the two UAVs (see Figure 16) that the streamlines from the left wingtip of the leading UAV interact with the streamlines of the right wingtip of the trailing UAV obviously. Because of the opposite direction of the streamline rotation, the right wing vortex of the trailing UAV is disturbed and suppressed. From the viewpoint of conservation of energy, the energy of
The vortex effect on the rolling moment of the trailing UAV in the close formation flight is shown in Figure 9(d). As the trailing UAV moves inboard in the lateral direction, the vortex effect on the trailing UAV produces an increasing left rolling moment. At about 0.875b lateral spacing, the left rolling moment of the trailing UAV reaches the maximum. Further inboard, the rolling moment decreases and eventually reverses direction. At about 0.8b lateral spacing, the rolling moment changes sign and increases with further wingtip overlap. The right rolling moment of the trailing UAV reaches the maximum at 0.5b lateral spacing, almost three times in magnitude over the greatest left rolling moment. From the vertical direction, we can see that the trailing UAV receives the greatest vortex effect when it is level with the leading UAV, and the vortex effect decreases as the vertical distance between the UAVs increases.

From the front analysis, we can see that the pressure distribution on the left and right wing of the trailing UAV is uneven owing to the effect of the vortex from the leading UAV, which leads to unbalanced lift distribution on the left and right wing of the trailing UAV. As shown in Figure 17(a), the lift on the left wing is higher than that on the right wing when the lateral spacing is 0.5b, thus leading to the right rolling moment. When the lateral spacing is 1.25b (see Figure 17(b)), both the left and right wing are under the upwash flow of the leading UAV’s wingtip vortex, but the right wing is more close to the vortex core, so the lift on the right wing is higher than that on the left wing, thus leading to the left rolling moment.

Figure 9(e) shows the vortex effect on the pitching moment of the trailing UAV in the close formation flight. The trailing UAV encounters an increasingly nose-down pitching moment as the trailing UAV moves inboard in the lateral direction. At 0.875b lateral spacing the pitching moment changes slope and then decreases sharply. At about 0.8b lateral spacing, the pitching moment changes sign. Further inboard, the nose-up moment increases and eventually reaches maximum at 0.5b lateral spacing. From the vertical direction, we can see that the vortex effect on the pitching moment is very strong at the level position and decreases as the vertical distance between the UAVs increases.

Figure 9(f) shows the vortex effect on the yawing moment of the trailing UAV in the close formation flight. The yawing moment (nose left) increases slightly as the trailing UAV...
moves inboard in the lateral direction and reaches maximum at 0.875b lateral spacing. Further inboard, the yawing moment decreases sharply and becomes nose right at about 0.8b lateral spacing. The nose right yawing moment is about three times in magnitude over the largest nose left yawing moment at about 0.5b lateral spacing. From the vertical direction, the vortex effect on the yawing moment is very strong when the two UAVs are at the same height, and the effect becomes relatively weaker as the vertical distance increases.

4. Aerodynamic Analysis of the Close Formation Flight for Three UAVs

The aerodynamic interference effect of the close formation flight for two UAVs is analyzed in the front part, and the optimal position that the lift-to-drag ratio of trailing UAV has the maximum value is obtained. In order to explore the preliminary application of the aerodynamic benefits in close formation flight for multiple UAVs, three different types of three UAV formations are designed based on the optimal position. The three UAV formation types are inverted-V formation, V formation, and echelon formation. For the convenience to comparatively analyze the formation flight interference effects and aerodynamic benefits, all the UAVs in three formation types are referred to as UAVs “A”, “B”, and “C”. Figure 18 shows the schematic diagram of the three UAV formation types.

Figure 19 shows the lift-to-drag ratio of the three UAVs in the three different formation types. UAV A in all three formation types locate at the front of the formation; the lift-to-drag ratio of the three UAVs is almost the same as that of UAV in single flight since the aerodynamic interference from other UAVs is negligible. UAV B in inverted-V formation and echelon formation have the same lift-to-drag ratio; this is because both of the two UAVs are positively affected by the left wingtip vortex of the leading UAV. The position of UAV B is symmetrical with UAV A in the V formation, and the aerodynamic interference from other UAVs can also be ignored, so the lift-to-drag ratio is the same as UAV A.

The most distinctive features of all the three formations are reflected by UAV C owing to the stronger and more complex vortex effect from the wingtip of the other UAVs. Figure 20 shows the vortex core region of the three UAVs in the three different formation types; it can be clearly seen that the wingtip vortexes are suppressed due to the favorable effect of wingtip vortex from UAVs ahead. In inverted-V formation, UAV C is located at the symmetrical position of UAV B and affected by the right wingtip vortex of UAV A, so the lift-to-drag ratio is the same as UAV B. The lift-to-drag ratio of UAV C in echelon formation is higher than that in inverted-V formation. The reason for this is that both of the left wingtip vortexes shed from UAV A and UAV B in echelon formation have a favorable effect on UAV C. However, unlike the UAVs in the optimal position, the increase of the lateral and longitudinal spacing between UAV A and UAV C leads to the decrease of the favorable vortex effect, so the lift-to-drag ratio of UAV C in echelon formation is only slightly improved compared with UAV C in V formation, with the amount of 18.4. UAV C in V formation is located at optimal
In conclusion, the V formation is more difficult to avoid collision for the trailing UAV when formation problems occur. If all the three UAVs execute the same mission, inverted-V formation and echelon formation are a suitable choice. Like the migration of wild goose, when the leading goose gets tired, it rotates back into the formation and another goose flies at the leading position, and the UAVs can also change the position in turn to take advantage of the wingtip vortex from the others in the formation; thus the range and endurance of all the UAVs can be improved. By comparative analysis, the utilization of the wingtip vortex in echelon formation is more effective than inverted-V formation. However, the inverted-V formation will be a more reasonable choice when considering compactness, cooperativity, and low observability of the formation.

5. Conclusions

This paper numerically simulates the aerodynamic characteristics of the close formation flight and obtains the following results:

1. There is strong aerodynamic interference between the two UAVs in the close formation flight, and the effects on the aerodynamic characteristics of the trailing UAV are mainly derived from the wingtip vortex of the leading UAV.

2. The incremental aerodynamic forces and moments of the trailing UAV vary with the lateral and vertical spacing between the two UAVs, and the optimal position where the trailing UAV obtains the maximum lift-to-drag ratio is obtained at the point of z/b=0 and y/b=0.75, with a maximum incremental value of 3.34 (25.4% increment compared to single flight). This value varies with the configuration of the UAVs. If the UAV has a vertical tail and a horizontal tail, the flow field behind it will be more complicated. The wingtip vortexes from the vertical tail and the horizontal tail of the trailing UAV interact with the wingtip vortex, which will increase the difficulty of finding the optimal position.

3. The aerodynamic characteristics of the close formation for three UAVs can be improved when the formation is designed based on the optimal position; the lift-to-drag ratio of UAV C in V formation reaches 22.36, almost 70% increment compared to single flight.
The close formations for three UAVs have different characteristics and advantages; it can be selected according to the mission category in operational application.

Data Availability

The data of the CFD calculation results used to support the findings of this study are included within the supplementary information files.

Conflicts of Interest

There are no conflicts of interest.

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Supplementary Materials

The supplementary files are the CFD calculation results of the effects of the leading UAV on the trailing UAV in the close formation flight. (Supplementary Materials)

References


