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PROCEEDINGS

Effects of Unequal Individual Spacing on the Aerodynamic Performance of Three Flapping Wings in Tandem

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ABSTRACT

Many species generally choose highly organized movements to gain more performance advantages rather than alone in the animal world, such as V-formation and line formation in birds. Understanding the aerodynamic characteristics and flow variation of multi-flapping wings in formation flight could be applied to the formation design of new bionic flapping-wing aircraft. In this paper, the effects of unequal individual spacing on the aerodynamic performance and flow mechanism of three-dimensional three-flapping wings flying in tandem formation are investigated numerically at a low Reynolds number. The simulations include small and large spacings, as well as cases with equal and unequal spacings of adjacent individuals. The results show that unequal individual spacing has a significant effect on the aerodynamic performance of groups and individuals in tandem formation flight. In addition, exchanging the spacing of adjacent individuals in the same formation would not change the aerodynamic performance of the group, but would dramatically change the benefit distribution of individuals. A detailed analysis of the flow field variations reveals the connection between individual spacing changes and flow mechanism changes. It also explained whether the narrow channel effect in the downstroke and the wake capture effect in the upstroke could be applied in tandem formation flight, subject to the variation of individual spacing.

KEYWORDS

Multi-flapping wings; aerodynamic performance; low Reynolds number; wake

1 Introduction

It had been a long-held thought that many flying and swimming animals can consume less energy and travel long distances through highly organized groups movement. In nature, the phenomenon of formation movements of schools of fish and flocks of birds is often observed and studied [1-4]. The initial goal of these researches, in addition to providing insight into biological formation motion, is to gain inspiration that will contribute to the optimal formation motion design of new bionic air or underwater vehicles. Understanding the aerodynamic/hydrodynamic benefits of biological formation motion and the advantages in terms of energy consumption is now becoming a focus of interest.

The aerodynamic performance of multi-flapping wings in tandem formation is greatly influenced by the spacing between adjacent individuals [5,6]. In previous studies of multi-flapping wings tandem formation, the adjacent individual spacing was considered to be the same. However, the organisms are more aware of the basic concept of promoting their advantage and will choose some advantageous positions to profit [3,4]. This suggests that in a flight formation, adjacent individuals are not necessarily equally spaced in order to obtain the desired benefit. Therefore, it is necessary to think about whether the unequal spacing of adjacent individuals in formation movements significantly affects the aerodynamic performance of groups and individuals. In addition, the adjacent individual spacing was relatively small in previous works [6], it is still questionable whether the corresponding flow mechanisms can still be applied at larger individual spacing. The answers to these questions may not only provide biologists with more perspectives to understand biological tandem formation flight, but also inspire engineers to design new multi-flapping vehicles as well as formation design of aircraft. Based on the previous work [6], this paper further numerically investigates the effect of adjacent unequal individual spacing on the aerodynamic performance of the tandem formation flight with three-dimensional three-flapping wings.

2 Models and Methods

In the present research, we control the number of wings to be three in tandem formation and all wings share the same shape. The wing shape is a flat plate with rounded leading and trailing edges with a thickness of 3% of the local chord length, which originated from a typical insect (*Eristalis tenax*). The aspect ratio R/c = 3.75 and r_2 = 0.56R (R, c, and r_2 are wing length, mean chord length, and radius of gyration of the wing, respectively) of the wing model in Fig. 1. To distinguish the three wings, we named the front, middle, and rear wings W1, W2, and W3, respectively. In tandem formation, each individual performs the same motion, in which the wing flaps around the wing root in the air and the wing root moves forward horizontally with velocity (V) to simulate the forward flight (see Fig. 1). Wing motion is the same as our previous study [6], including the stroke position angle (ϕ) and the rotation angle (ψ).

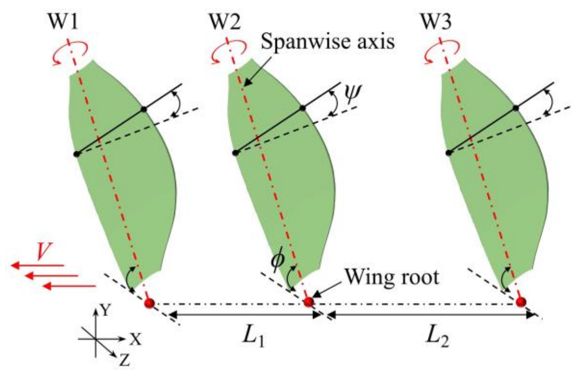

Figure 1: Schematic diagram of three flapping wings in tandem formation flight.

In the tandem formation of three flapping wings, the distance between adjacent individual wing roots in the X-direction is modified to form different configurations. The distance between W1 and W2 roots is defined as L_1, and the distance between W2 and W3 roots is defined as L_2 (see Fig. 1). We represent a specific configuration case by (L_1, L_2), and the values of L_1 and L_2 include 1.5c, 2c, 2.5c, 3c, 4c, 5c, and 6c. In this way, 49 different combinations of L_1 and L_2, i.e., 49 different formations, can be formed.

The governing equations of the flow are the three-dimensional (3D) incompressible unsteady Navier-Stokes equations. Reynolds number (Re) is set to be 200 in the following simulations, and the flow around the wing is considered to be laminar. The governing equations are solved by the in-house solver which is based on the finite difference method. For more information on the solver and accuracy verification, please refer to Ref. [6,7]. Moving overlapping grid technology is used because of the independent flapping of multiple wings. Grid systems include wing grid (O-H type) and Cartesian background grid (see Fig. 2). For a detailed study of the numerical variables such as grid size, domain size, time step, etc., please refer to Ref. [6].

We define the wing lift (L) as the component of force perpendicular to the incoming flow and the wing thrust (T) as the component of force in the direction of forward flight velocity. The aerodynamic power (P_a) was calculated as the product of the aerodynamic moment and the angular velocity. The lift, thrust, and aerodynamic power coefficients are defined as follows: $C_L = 2L/\rho U^2 S$, $C_T = 2T/\rho U^2 S$, and $C_{Pa} = 2P_a/\rho U^3 S$, where S is the area of one wing, ρ is the air density. The lift and thrust efficiencies were then defined as $\eta_L = \overline{C_L}/\overline{C_{Pa}}$ and $\eta_T = \overline{C_T}/\overline{C_{Pa}}$, respectively. $\overline{C_L}$, $\overline{C_T}$, and $\overline{C_{Pa}}$ are cycle-averaged C_L, C_T, and C_{Pa}, respectively.

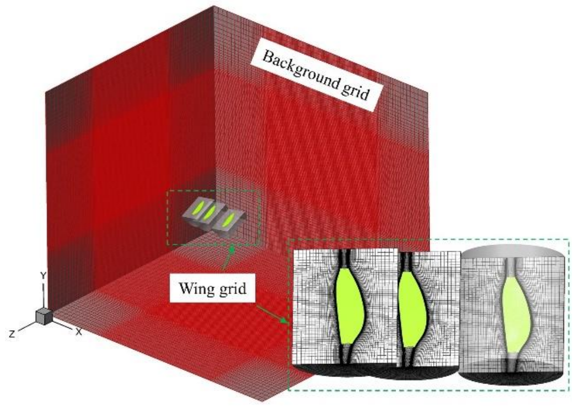

Figure 2: Portions of the computational grids

3 Results and Discussion

From Fig. 3, it can be seen that the individual spacing has a relatively small effect on the lift and lift efficiency of the group, while it has a significant effect on the thrust and thrust efficiency of the group. It is worth noting that the maximum thrust [(2*c*, 2*c*) case] and the maximum thrust efficiency [(2*c*, 2.5*c*) case] do not occur in the same tandem formation [See the red dots marked in Figs. 3(b) and 3(e)]. This also suggests that unequal individual spacing is necessary for the maximum thrust efficiency.

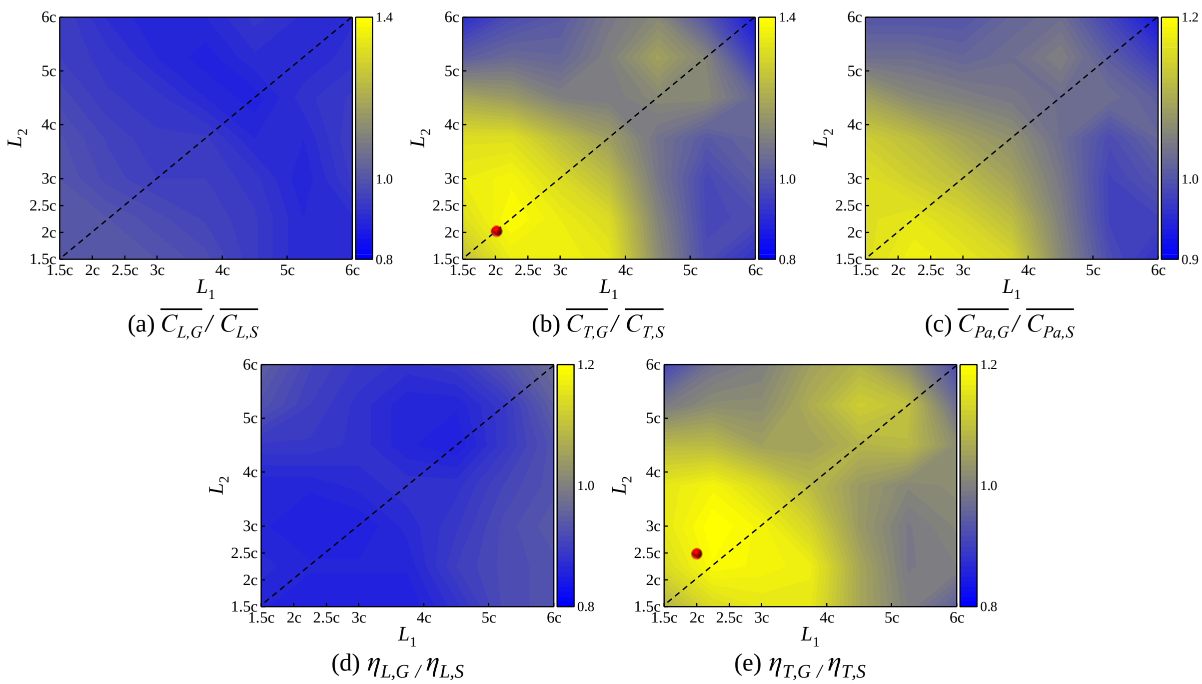

Figure 3: The ratio of the cycle-averaged lift (a), thrust (b), aerodynamic power (c), lift efficiency (d), and thrust efficiency coefficients (e) of the three flapping wings group to that of the single-wing for all tandem formation configurations. Subscripts "G" and "S" in the symbols represent the three-wing group and single wing, respectively.

We also found it interesting that the difference in the overall aerodynamic performance between the (L_1, L_2) case and (L_2, L_1) case is very small (less than 9%). This indicates that two different tandem formation configurations can produce the nearly same overall aerodynamic performance. It can also be interpreted that in the tandem formation flight of three flapping wings, the distance from the leader to the last follower is fixed, but the position of the middle individual can be changed dynamically. This adjustment does not affect the aerodynamic performance of the whole group but may lead to a large difference in the aerodynamic performance of the individuals.

To illustrate the differences in the aerodynamic performance of the individuals, we selected the case of (1.5*c*, 3*c*) and (3*c*, 1.5*c*) to illustrate them in detail. For simplicity, the former is defined as case A and the latter as case B. Firstly, for case A, it can be seen from Fig. 4(a) that the lift and thrust of each individual differ significantly. Compared to single wing (SW), the lift of W1 increased by 23%, while the lift of W2 and W3 decreased by 14% and 12%, respectively. The amount of change in thrust is greater than the amount of lift change. Compared to SW, the thrust of W1 and W3 increased by 27% and 76%, respectively, while the thrust of W2 was reduced by 17%. It can be seen that W3 gets the best thrust advantage, followed by W1, while W2 suffers badly.

Then, we analyze case B. From Fig. 4(b), we can see that compared with SW, the lift and thrust of W1 are slightly improved, increasing by 6% and 4%, respectively; the lift and thrust of W2 are greatly improved, increasing by 15% and 59%, respectively; while the lift of W3 is reduced by 28% and the thrust is increased by 37%. Compared with case A, the aerodynamic forces of W1 and W3 are reduced, and only the aerodynamic forces of W2 are improved. It suggests that when flying in a tandem formation with three flapping wings, fixing the distance between the leader and the last follower and changing the position of the middle individual will not change the aerodynamic force of the group but will redistribute the profitability of each individual. The remarkable difference in the aerodynamic performance of each individual also reflects the fact that they are disturbed by the surrounding flow field very differently.

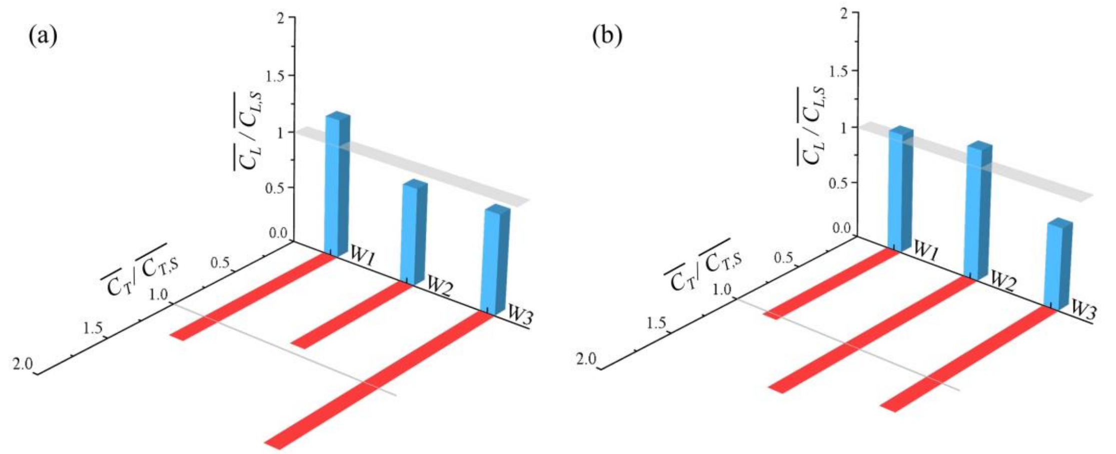

Figure 4: The ratio of the cycle-averaged lift and thrust coefficients to the single wing for each individual in (a) case A and (b) case B.

We explain the effect of individual spacing on the flow mechanism by analyzing the instantaneous force profiles and the associated flow structure of several cases. The variation in individual spacing significantly affects the flow around the three flapping wings, which results in aerodynamic differences. In the downstroke, the small individual spacing is detrimental to the leading-edge vortex (LEV) growth of the latter, which causes a smaller aerodynamic force; for the larger individual spacing, the narrow channel effect does not apply but is influenced by the downwash accompanying the wake, leading to a lower aerodynamic force. In the upstroke, the small individual spacing leads to the rear wing cutting off the vortex ring of the front wing to form different shed vortices, which in turn affects the rear wing to benefit differently; the larger individual spacing does not allow the rear wing to cut off the vortex ring of the front wing so that the rear wing fails to profit.

4 Conclusion

Considering the complexity of biological formation motion, we have enriched our previous research work. The effects of unequal individual spacing on the aerodynamic performance and flow mechanism of three-dimensional three-flapping wings flying in tandem formation are numerically investigated. The results show that the thrust and thrust efficiency of groups were improved significantly in the range of individual spacing less than or equal to 4*c*, out of which the aerodynamic benefits decreases. It was also found that the maximum thrust and thrust efficiency did not occur in the same case, which also highlight the important role of unequal individual spacing. Moreover, for the three-flapping wings tandem formation, adjusting the position of the middle wing does not change the aerodynamic performance of the whole group, but can dramatically affect the distribution of individual profitability. In the analysis of flow variation, the connection between individual spacing variation and unsteady flow variation is revealed, and the influence of individual spacing on tandem formation flight is more deeply understood. The present study on the effect of unequal individual spacing on the aerodynamic performance of multi-flapping wings in tandem formation flight has potential applications in bionic vehicle formation flight.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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