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Performance Analysis of Flapping Wings in Formation Flights

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Abstract. In this paper, we investigate the aerodynamic aspects of formation flights. We do so by simulating the flow over flapping wings flying in grouping arrangement and in proximity of each others using the unsteady vortex lattice method. The results show that flying in V-shaped line formation at optimal spacing enables significant increase in the lift and thrust and savings in the power consumption. This is mainly due to the interaction between the trailing birds and the previously-shed wake vorticity from the leading bird.

Keywords: Flapping wings; formation flight; unsteady vortex lattice method; wake capture.

1 INTRODUCTION

Self-organization is a well-established property of nature that occurs in several biological systems, such as fish joining together in schools and birds flying in line and cluster formations. In the latter organized systems, a global pattern arises from the interactions between each component. The current general understanding of these interactions and aerodynamics mechanisms involved in such organized flights is based on field observations [1, 2, 3, 4] and the interpretation of these observations is performed using simplified aerodynamic models [5, 6, 7]. Migratory birds, which usually fly for long distances without stop and feeding, were observed to get benefit from such grouping arrangement to carefully manage flight energy consumption. All these observations of such fascinating phenomenon motivate the computational assessment of the associated aerodynamic aspects. This would provide guidance for the development of new air vehicles designed to conduct missions involving close proximity formation flights, multi-vehicle interaction, and cooperation.

In this paper, we conduct a computational study of flapping wings in line formation flight to discern the associated aerodynamic mechanisms. Towards this end, we use the three-dimensional version of the unsteady vortex lattice method (UVLM) to simulate the flow over flapping wings and evaluate the aerodynamic forces and power. UVLM has the capability to capture unsteady effects associated with the previously-shed wake vorticity, as well as wake-capture effects, both of which present important aerodynamic aspects in formation flights. We demonstrate the importance of these aspects in offering power saving and significant increase in lift and thrust generation.

2 AERODYNAMIC MODELING

A potential flow solver based on the unsteady vortex lattice method (UVLM) is used for the prediction of the unsteady aerodynamic forces and moments. This allows us to investigate the interactions between flapping wings in formation flight and determine their effect on flight efficiency in terms of generation of aerodynamic loads and power consumption. The unsteady vortex lattice method computes the loads generated by pressure differences across the wing surface resulting from acceleration- and circulation-based phenomena. This accounts for unsteady
effects such as added mass forces, the growth of bound circulation, and the wake. UVLM applies only to ideal fluids, incompressible, inviscid, and irrotational flows where the separation lines are known a priori. For more details on the current implementation of UVLM along with verification and validation studies, the reader is referred to [8, 9]. In our simulations, we account for the interactions of multiple wings. In Figure 1, we plot flapping wings in formation flight and their associated wakes where the color levels denote the vorticity circulation strength. The vorticity in the wake was generated on and shed from the wing at an earlier time. Thus, examining the wake pattern and vorticity distribution can be helpful to gain insight into the generation of aerodynamic quantities. Pockets of highest circulation are observed in the wake aft of flapping wings during the downstroke. Clearly, the trailing flapping wings intercept the wake created shed from the leading ones and then can take advantage of this aerodynamic aspect to improve their performance as will be discussed in the next section.

Figure 1: Wake patterns of the flapping wings in formation flight. Contour color levels denote the vorticity strength of the wing and the wake. The wake has been moved back for the sake of differentiating it from the wing.

3 MULTI-FLAPPING WING FORMATION FLIGHT: RESULTS AND DISCUSSION

In this section, we present results of flapping wings interacting with an incompressible uniform flow and flying in line formation. Each wing has a rectangular shape with an aspect ratio of six and a NACA 83XX cross-sectional profile as studied previously by Ghommem et al. [9]. As observed in nature [1, 2, 3, 4], birds flying in line formation follow an organized pattern in V-shape. As such, we consider three avian-like flapping wings in V-formation flight as shown in Figure 2. The relative position between the leading bird and the trailing bird is defined by $(x_{rel}, y_{rel})$. The flapping motion about the wing root (identical for all wings) is assumed symmetric and prescribed as:

$$\phi(t) = A_\phi \cos(\omega t),$$

where $\phi$ is the flapping angle and the flapping amplitude $A_\phi$ is set equal to $45^\circ$. Furthermore, the wing root is placed at a fixed angle of attack (pitch) of $5^\circ$ and a reduced frequency equal to 0.1 is used. The reduced frequency is defined as

$$\kappa = \frac{\omega}{U_\infty c},$$

where $\omega$ is the flapping frequency, $U_\infty$ is the freestream velocity, and $c$ is the wing chord length. The wing shape and flapping configuration adopted in the present study can be representative of large bird flights [10]. As for numerical simulation, a particular care was made when selecting the mesh and time step sizes. Each flapping wing
is discretized into 10 panels along the spanwise direction and 24 chordwise panels, providing $N \times 240$ vortex rings for the UVLM solver, where $N$ is the number of wings. A small time step of $\Delta t = 2\pi/(120 \omega)$ is selected (i.e., 120 time steps per flapping cycle). Under this setting, the aerodynamic quantities were observed to converge. For three birds (avian-like flapping wings), the total time taken by a workstation featuring Intel® Xeon® CPU X5650 2.67 GHZ processor to run the serial version of the solver (implemented in Fortran) for one flapping cycle is 10 mn 34 s. Clearly, the execution time associated with the UVLM solver along with its capability to capture the unsteady effects of the wake make this aerodynamic tool a good candidate to analyze the behavior and performance of multiple flapping wings flying in close proximity.

The baseline case of the present study corresponds to a single flapping vehicle isolated from any interaction with other wing or wake vorticity. The lift, thrust, and aerodynamic power coefficients along with the propulsive efficiency obtained for the baseline case are given in Table 1.

Table 1: Baseline case results. The overline denotes averaged values over one flapping cycle.

<table>
<thead>
<tr>
<th>Lift coefficient</th>
<th>Thrust coefficient</th>
<th>Power coefficient</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L^\infty$</td>
<td>$C_T^\infty$</td>
<td>$C_P^\infty$</td>
<td>$\eta^\infty$</td>
</tr>
<tr>
<td>0.755</td>
<td>0.0348</td>
<td>0.1435</td>
<td>0.2428</td>
</tr>
</tbody>
</table>

Next, we examine the effect of the relative position between the leading bird and the trailing bird on the aerodynamic performance of the latter bird. In Figure 3(a), we plot the variations of the ratio $C_L/C_L^\infty$ with the lateral spacing distance $y_{rel}$, where the superscript $\infty$ refers to the aerodynamic quantity obtained for the baseline case (solo flight). The range of variations of $y_{rel}$ was selected so that the wings of bird 2 and bird 3 shown in Figure 2 don’t intercept. Clearly, bird 2 flying behind the leading bird 1 generates more lift force than achieved when flying alone. As a result, the flapping wings of bird 2 can be placed at a lower angle of attack or beat at lower frequency than the leading one while still maintaining the same lift, resulting in decreased energy expenditure. We observe a maximum increase of lift of 7% at $y_{rel} \approx 5$ c. Beyond that spacing distance, as bird 2 moves more and more outboard bird 1 (i.e., if $y_{rel}$ is increased), the interaction effect is damped and the lift ratio tends to one (i.e., get back to the amount of lift obtained when flying alone).

In Figure 3(b), we show the variations of the ratio $C_T/C_T^\infty$ with the lateral spacing distance $y_{rel}$. A significant increase in the induced thrust is observed when flying in formation. This increase reaches its maximum of 40% at $y_{rel} \approx 5$ c. The increase observed in the aerodynamic loads generated by birds flying in close proximity formation can be explained by the their interaction with the previously-shed wake of the leading bird. In fact, a trailing bird flying in the region of the wake vortices left by the leading bird experiences a forward tilted lift vector which, effectively reduces the induced drag of the trailing bird while simultaneously increasing its lift.

The variations of the power ratio $C_P/C_P^\infty$ with the lateral spacing distance $y_{rel}$ are shown in Figure 3(c). Clearly,
flying in formation enables power saving that reaches its maximum of 6.5% at \( y_{rel} \approx 4.85 \) c. As would be expected, isolating the flapping wings from interacting with other wings and wakes (i.e., increasing the spacing distance \( y_{rel} \)), the power ratio tends to one. At the optimal spacing distance, the propulsive efficiency of bird 2 reaches a value of 0.362; that is, an increase of about 50% as compared to a single bird in solo flight. The trailing birds, by intercepting the wake generated off the wing trailing edges and tips of the leading bird (see Figure 1), recapture energy lost to the wake. This phenomenon is usually referred as wake capture which is a well-established mechanism observed in hovering flights of insects and Humming birds [11, 12]. The wake shed behind a flapping wing contains energy provided to the surrounding fluid in the form of momentum and heat. So, the flapping wing gets back some of this energy and employ it to improve its flight performance in terms of power consumption and lift generation.

4 CONCLUSION

In this work, we used a potential flow solver based on the unsteady vortex lattice method to simulate flapping wings in formation flight. In our simulations, we accounted for the aerodynamic coupling between flapping wings along with their interactions with the wake vorticity. Our numerical analysis is motivated by experimental observations of migratory birds. The results show that flying in V-shaped formation at optimal spacing yields significant increase in the lift and thrust and savings in the power consumption. This can be explained by the inherent interaction between the trailing birds and the previously-shed wake vorticity from the leading bird.

REFERENCES