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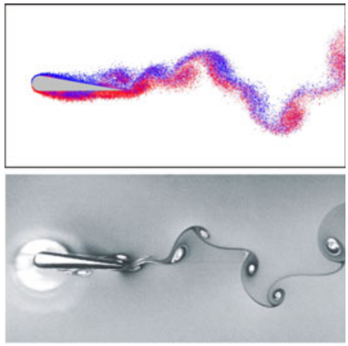
Footprints of a flapping wing



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Birds have to flap their wings to generate the needed thrust force, which powers them through the air. But how exactly do flapping wings create such force, and at what amplitude and frequency should they operate? These questions have been asked by many researchers. It turns out that much of the secret is hidden in the wake left behind the flapping wing. Exemplified by the study of Andersen *et al.* (*J. Fluid Mech.*, vol. 812, 2017, R4), close examination of the flow pattern behind a flapping wing will inform us whether the wing is towed by an external force or able to generate a net thrust force by itself. Such studies are much like looking at the footprints of terrestrial animals as we infer their size and weight, figuring out their walking and running gaits. A map that displays the collection of flow patterns after a flapping wing, using flapping frequency and amplitude as the coordinates, offers a full picture of its flying 'gaits'.

Key words: flow–structure interactions, swimming/flying, vortex streets

1. Introduction

The dinosaurs are long gone, but their fossilized footprints are still around. Scientists are able to infer the size, weight and sometimes the running gaits of these terrestrial animals by closely examining their footprints. The spacing between the footprints and their depth and angles reflect much information about how these animals interacted with the ground many million years ago.

When a bird flies by in the fluid that we call air, the perturbed gas moves and rotates in some orderly fashion, somewhat like footprints cast into the muddy ground by land animals. Such wakes or flow structures are quite short lived, they disappear quickly due to diffusion or are destroyed by wind. Making transparent air and its motion visible to our eyes is challenging but can be achieved with smoke or lightweight powder that marks the air temporarily. If the details of air flow structures around a flying bird are made visible, a fluid dynamicist can extract much information

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about how the bird generates lift and thrust forces and how quickly it flies. It is thus almost a necessity to show flow structures when studying how birds fly and how fish swim (Müller *et al.* 1997); the latter is almost an identical problem for many scientists since the physical mechanisms that produce forces and the mathematical handling of the two systems are similar. The equivalence between fish swimming and bird flying was made pleasantly visible, graphically, by the Dutch artist Maurits C. Escher in his two 1938 woodcuts, Sky and Water I and II, as he morphed flying birds into swimming fish.

To focus on the key element of the locomotion problem, the study of how birds fly is often simplified to studying how a flapped aerofoil interacts with an open flow. It turns out that the wake structure resulting from the interaction between the flapping wing and the initially uniform flow reveals a lot of clues that a fluid dynamicist will find useful. For instance, if an aerofoil or wing is flapped slowly, with its top speed much less than the open flow speed, the wake often forms a classical von Kármán vortex street, a signature flow structure found after an immobile object sitting in a flow (von Kármán & Burgers 1935). There, the vortex dipoles formed by any two adjacent fluid vortices will point, at least partially, in the upstream direction. This indicates that the open flow has been slowed down by the gentle flapping wing. If the flapping speed is much increased, however, by either increasing the flapping frequency or amplitude or both, the vortex street will look different. The vortex dipoles now behave like a series of fluid puffs generated at the trailing end of the wing and getting pushed off into the downstream direction. This increase in the fluid speed downstream of the flapping wing is directly associated with the generation of a net thrust force, which is useful for bird flight. Here, the thrust-producing wake is often termed the inverted von Kármán vortex street.

However, the exact mechanism by which a flapped wing reverses the flow structure, thus turning a von Kármán vortex street into an inverted von Kármán vortex street, and how the net force experienced by the wing changes from being resistive to propulsive, is not known (Vandenberghe, Zhang & Childress 2004; Godoy-Diana, Aider & Wesfreid 2008).

2. Overview

The article by Andersen *et al.* (2017) presents a detailed and revealing investigation of the rich variety of wake structures of a flapping wing, and relates the changes in the wake structure to the transition from drag to thrust.

This study consists of numerical simulations and laboratory experiments. The numerical results were obtained using a particle vortex method (Walther & Larsen 1997). There, many virtual particles are seeded into the flow where the speed gradient or shear is strong. These vortex particles, as marked in two colours depending on the sign of the local fluid rotation (vorticity), follow the flow and diffuse over time, revealing the wake structures. The laboratory experiment was conducted in a flowing soap film, a nearly two-dimensional water tunnel (Zhang *et al.* 2000; Rutgers, Wu & Daniel 2001) that not only offers high-speed laminar flows but also provides a convenient flow visualization platform. The thinness of the flowing film, of the order of a few micrometres, makes it possible for us to see the minute thickness changes through optical interference. Advected by the main flow and spun by flow rotation, soap films often render great flow details.

From the two very different methods, one experimental and the other computational, the authors have found two large collections of flow structures over a broad range

(*a*)
(*b*)

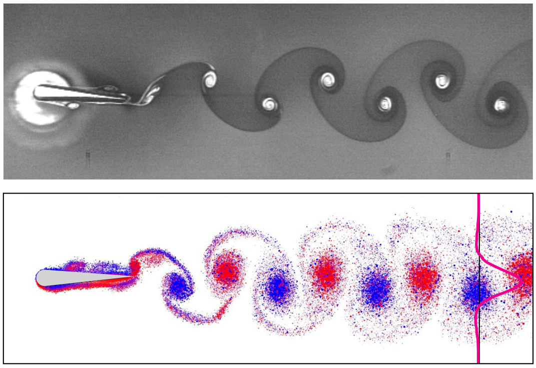

FIGURE 1. (*a*) A von Kármán vortex street produced from a pitching wing in a flowing soap film. When the wing is flapped slowly, it experiences a net drag force. (*b*) An inverted von Kármán vortex street, obtained by the particle vortex method, emerging as the wing flaps faster at the drag–thrust boundary. The red (blue) particles indicate counter-clockwise (clockwise) local fluid rotation and the magenta curve shows that a backward jet is being generated when compared against the black line that shows the unperturbed uniform flow profile. (Image courtesy of Andersen *et al.* (2017).)

of kinematic parameters. With each method, two different flapping gaits are studied: pitching and heaving. In the pitching gait, the wing is flapped or pivoted about its leading edge (Schnipper, Andersen & Bohr 2009). In the heaving gait, on the other hand, the wing is flapped transversely to the oncoming flow. The flow map is charted, with impressive precision against the flapping frequency and amplitude.

It is remarkable that computations and experiments produce nearly identical results under the same parameters. In a way, one method used in this study validates the other when their maps for the wakes of flapping wings overlap. The net force experienced by the wing can be computed from the simulations and a boundary, which demarcates net drag and net thrust, emerges.

By examining the wake map and the drag–thrust boundary, some meaningful conclusions can be made: (i) a von Kármán wake is always a drag wake; (ii) a thrust wake is (most likely) an inverted von Kármán wake. But wait, here comes some ‘fine print’ that immediately follows: (iii) a drag wake can sometimes be more complicated than a simple von Kármán wake and (iv) an inverted von Kármán wake is not necessarily a thrust wake, a point that has been made previously by other groups (Bohl & Koochesfahani 2009; Das, Shukla & Govardhan 2016).

One other important message a reader should take home is about the location of the drag–thrust boundary. In the pitching gait, this boundary follows closely the curve drawn by $2Af/U = 0.28$, where $2A$ is the peak-to-peak flapping amplitude, f the flapping frequency and U the oncoming flow speed. This dimensionless number, which is often referred to as the amplitude-based Strouhal number, compares the flapping speed with the oncoming flow speed. Here, if the flapping speed $2Af$ is low, the wing as a whole experiences a net drag. When the flapping speed is high enough, a thrust force is produced and an inverted von Kármán wake is found. Similarly, in the heaving gait, the flapping wing makes its drag–thrust transition at constant $2Af/U = 0.16$. The difference in the numbers, between 0.28 and 0.16, reflects the difference in the gaits used by the flapping wing.

Back to bird flight. Assuming that a bird flies at a constant cruising speed, the thrust force generated by the flapping wings has to be equal to the drag force experienced by the non-thrust-producing aerodynamic surfaces such as the head, body and the tail of the bird. The total drag force, and thus the thrust force, are not insignificant, which suggests that bird wings need to operate at a point well above the drag–thrust boundary. The Strouhal numbers taken by the birds should therefore be reasonably high.

3. Future

The above study demonstrates many common features and differences between two flapping gaits, pitching and heaving, used by a simple wing. In particular, a pitching wing needs to flap approximately 75 % faster than the heaving wing when it needs to cross the drag–thrust boundary. Naïvely, this seems to be the difference between the fluid areas swept by the flapping wing as it operates in the two different gaits. Perhaps it is time to ask in which gait the wing consumes less energy. In another words, it is time to find out how to drive the wings to produce useful thrust cost effectively.

As we come to know almost everything about a single flapping wing and its wakes, it is certainly time to ask how multiple flapping wings freely interact with each other. Indeed, orderly and stable patterns begin to emerge with a minimum 'bird flock' of two flapping wings (Ramananarivo *et al.* 2016), perhaps we will soon observe similar formations in fish schools (Weihs 1973).

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