

Multi-cored vortices support function of slotted wing tips of birds in gliding and flapping flight

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Abstract

Slotted wing-tips of birds are commonly considered an adaptation to improve soaring performance, despite their presence in species that neither soar, nor glide. We used particle image velocimetry (PIV) to measure the airflow around the slotted wing-tip of a jackdaw (*Corvus monedula*) as well as in its wake, during unrestrained flight in a wind tunnel. The separated primary feathers produce individual wakes, confirming a multi-slotted function, in both gliding and flapping flight. The resulting multi-cored wing-tip vortex represents a spreading of vorticity, which has previously been suggested as indicative of increased aerodynamic efficiency. Considering benefits of the slotted wing-tips that are specific to flapping flight combined with the wide phylogenetic occurrence of this configuration, we propose the hypothesis that slotted wings evolved initially to improve performance in powered flight.

1. Introduction

Slotted wing-tips, where the outer primary feathers split and spread vertically, are found in a wide range of birds and are considered an adaptation for efficient flight [1, 2]. Pronounced slotted configurations are facilitated by emarginations on the vanes of the outer primary feathers. The broader bases of the feathers overlap, limiting twisting and bending of individual feathers, while the narrower outer parts may deform independently of each other. Under aerodynamic loads the tips of the leading primaries rise above those of the trailing feathers, forming a staggered, non-planar, configuration. Previous research has focused particularly on the benefits of the vertical separation of the outer primaries in thermal soaring birds [1–4], where wing-tip slots were found to reduce induced drag (the cost of producing lift with finite wings, also referred to as vortex drag [5]). For a planar wing, induced drag is minimized by an elliptical lift distribution that comes with a spanwise uniform downwash distribution. Non-planar configurations can spread vorticity vertically,

abating high induced flows near the tip of a more uniformly loaded wing, allowing for reduced drag for a given wingspan [2, 6, 7] (see ESM). Extensive research into this subject since the early 20th century, has led to the development of wing-tip devices that are now common in passenger aircraft [7].

Many bird species that specialize in gliding flight do not exhibit a slotted wing-tip configuration, and have instead evolved high aspect ratio wings, an alternative solution to reduce induced drag, by extending their leading primaries to form a pointed wing, as seen in for example petrels and albatrosses (Procellariiformes) [8]. On the other hand, feather emarginations, indicating a slotted configuration, are found in many bird species that neither soar nor glide [9, 10], across the avian phylogenetic tree [8, 11] and among the most basal lineages of birds, including species that only fly occasionally (e.g. Tinamiformes, Galliformes). This suggests a more general function and benefit of a slotted wing-tip than for gliding flight only.

Here we test the hypothesis that slotted wing-tips spread vorticity in both powered and gliding flight. The

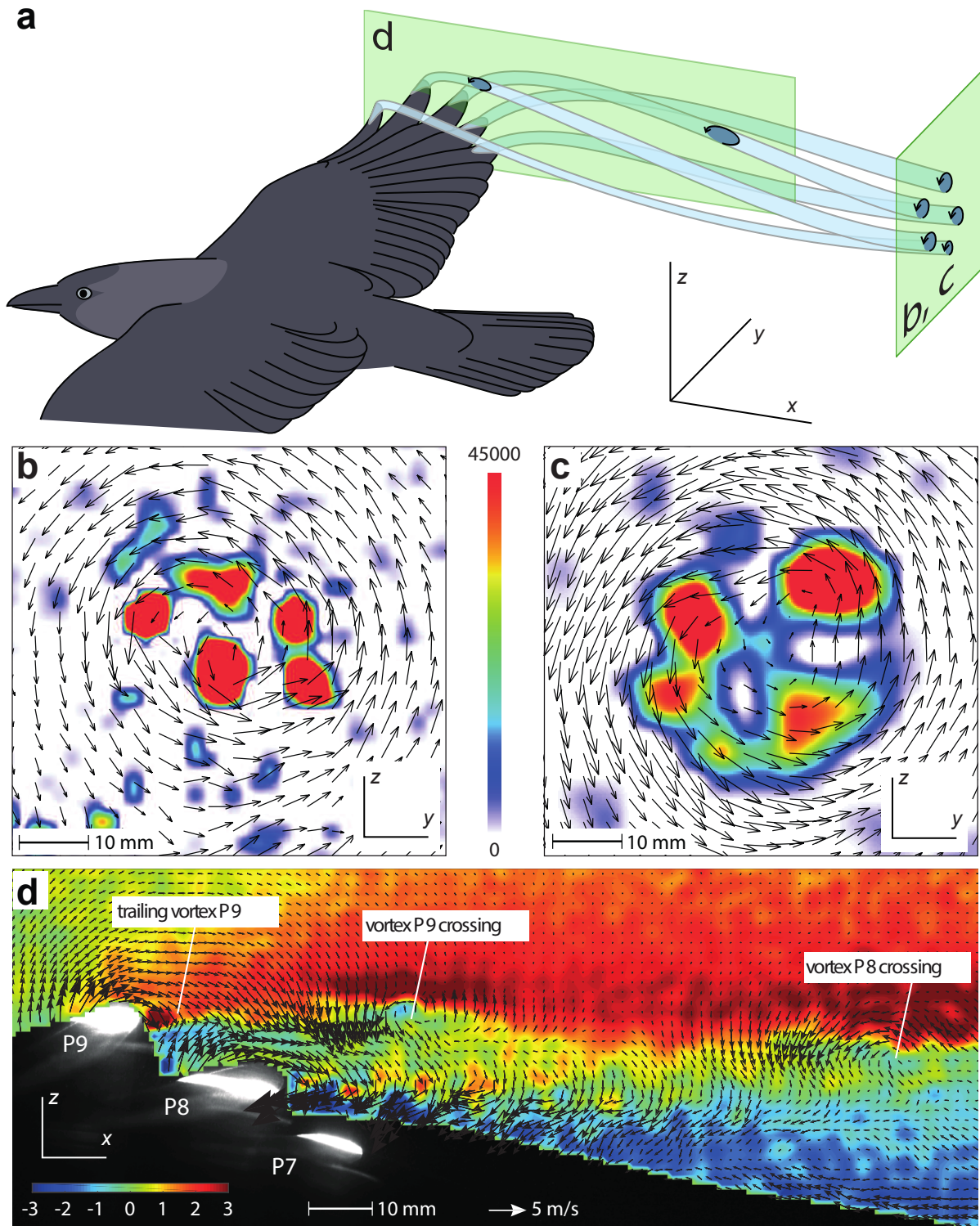


Figure 1: Flow visualization of the wingtip vortex for the slotted wing of a jackdaw. (a) Positioning of the measurement planes relative to the bird. Blue shapes schematically illustrate the structure of the vortex cores in the tip vortex. Right-handed coordinate system for reference with downstream aligned x-axis and horizontal y-axis; (b) Transverse flow field cutting the tip vortex in gliding flight. Vectors show velocity components perpendicular to the flight direction. Background colouring indicates swirl strength (scaled following the colour bar between b and c), a measure distinguishing vortices from shear layers (low intensity regions occurring randomly are due to measurement error); (c) as b, but at mid downstroke during flapping flight; (d) On-wing flow field at the slotted wing-tip in gliding flight, with vectors showing the vertical and streamwise components of the flow with the flight speed subtracted. The background colouring shows the spanwise velocity component (scaled following the colour bar), red pointing inboard. The background image shows the separated primary feathers 9, 8 and 7, illuminated by the laser sheet (white).

vertically separated outer primaries should then each shed their own wake and produce their own tip vortex [12] (figure 1a). To test this, we quantified the motion of the air in the wake behind a jackdaw (*Corvus monedula* L. 1758) flying in a wind tunnel using stereo Particle Image Velocimetry (see Methods). In gliding flight, we observed a tip vortex consisting of multiple distinct cores as shown in figure 1b. These cores are identified by separated peaks of high intensity swirl strength (imaginary part of the complex pair of eigenvalues of the velocity gradient tensor, distinguishing rotational motion from shear [13]), which, if originating from the separated primary feathers, supports the function of slotted wingtips as non-planar wing-tip devices [2, 12]. Induced drag measured in gliding flight indicated an efficiency of the main wing between 99.5% and 106.6% compared to an optimal planar wing [14] (see ESM). Such high efficiency suggests the wing acts as a non-planar lifting surface. The multiple cores are spiralling around a common centre, as can be inferred from the velocity field (figure 1b). The number of cores (five) in the wingtip vortex matches the number of slotted feathers of the wing-tip.

The wake shed during flapping flight showed a similar wingtip vortex structure as that found in gliding flight, composed of multiple cores (figure 1c), demonstrating that also during powered flight the separated feathers spread the vorticity of the tip vortex. This implies that an induced drag reduction may be realized in both flapping flight and gliding flight. In flapping flight the force and circulation distribution varies throughout the wingbeat, which negatively affects the span efficiency [15, 16]. This makes comparison to an idealized optimally loaded un-slotted wing in flapping flight challenging and beyond the scope of this paper.

To determine whether the multiple cores we found in the tip vortex originated from the individual feathers, we measured the velocity field on top of the wing in a streamwise plane, close to the wing-tip, where the feathers separate. The flow field is visualized in figure 1d, with the spanwise flow (out of plane) indicated by background colouring and the in-plane velocity (with flight speed subtracted) by vectors. A streamwise vortex coming from the tip of the ninth primary (P9) can be identified by the spanwise velocity component: an inward flow (positive) can be seen on top, and outward flow (negative) below the core, demonstrating the rotation of the P9 tip vortex. About 40 mm downstream of P9, this vortex crosses the measurement plane, indicated by the strong (in-plane) counter clockwise rotation, as it is convected inboard by the overall counter

clockwise rotation of the wing-tip vortex. The tip of the following feather (P8) is outboard of our measurement plane. Approximately 90 mm downstream of P8 its tip vortex crosses the measurement plane, identified by the strong (in-plane) counter clockwise rotation. The cores rotate at approximately 15 mm from the overall wingtip vortex centre (figure 1b), with a tangential speed of about 3 m/s (figure 1d). At a flight speed of 8.5 m s^{-1} , the cores have a wavelength of approximately 270 mm. This means that the vortex from P8 has travelled 1/3 cycle when it crosses the measurement plane, which agrees with the vertical location of the crossing. From these observations, we conclude that the multiple cores of the tip vortices, found in the wakes of the gliding and flapping bird, originate from the separated primary feathers.

Besides reducing induced drag, slotted wing-tips may have additional aerodynamic benefits specific to flapping flight. During the downstroke, the air approaches the wing-tip at a high angle of attack, which would make the distal part of the wing prone to stall. To reduce the angle of attack, the wing-tip needs to twist (washout), like the blade of a propeller. Instead of twisting the entire wing, which would require structurally challenging bending of the feather shafts, slotting allow feathers to twist individually [1]. This allows for a broader wing-tip, and thus a higher loading of the outboard wing, which is most efficient for thrust production [17] and as such beneficial for powered flight. Additionally, a multi-slotted wing can increase the maximum lift coefficient of an aerofoil [18], thereby maximizing the available thrust. Being able to generate high thrust is beneficial e.g. for predator evasive manoeuvres, including take-off in ground living species, and would therefore be highly selected for.

In this study, we demonstrate that slotted wing-tips cause vortex spreading—the mechanism behind reduced induced drag—in both gliding and flapping flight of a jackdaw. In the light of additional aerodynamic advantages unique to flapping flight (e.g. reduced risk of stall and increased thrust), and the abundance of slotted wing configurations across the phylogeny of modern birds, we propose the hypothesis that the slotted wing-tip originally evolved to improve flapping flight performance. Testing this hypothesis requires a wide comparative analysis of feather morphology and flight style and further studies of the aerodynamic details of slotted wing-tips during flapping flight.

2. Methods

2.1. Study species

A young jackdaw was taken from a study colony near Revingehed, Skåne, Sweden (June 11, 2013), and trained to keep position when flying in the wind tunnel. For more details see reference [14]. Following Pennycuick [19], maximum wingspan was measured from the bird in the hand, being $bw = 0.67$ m and wing area was determined from a tracing of the wing: $Sw = 0.0652$ m² (including both wings and the area between the wing roots). Body mass was measured daily and was stable around 0.215 kg.

2.2. Experimental setup

We used the low-turbulence tiltable wind tunnel at the Department of Biology, Lund University, Sweden [20], which has an octagonal test section with a width of 1.2 m and a height of 1.08 m. For gliding flight experiments, the tunnel was set at a glide angle of 6 degrees. For powered flight the wind tunnel was horizontal. In all reported cases the airspeed was in the range 8–8.5 m s⁻¹. The velocity field in a plane perpendicular to the free stream flow in the wake behind the bird was measured using a stereo Particle Image Velocimetry (PIV) system recording 640 frame-pairs per second. A 527 nm diode pumped LDY304PIV laser (Litron Lasers Ltd, Rugby, England) was used to illuminate particles (~ 1 μ m) in a sheet (~ 3 mm thick). For wake experiments two LaVision Imager pro HS 4M (LaVision GmbH, Göttingen, Germany) high speed cameras 2016 \times 2016 px in stereo configuration were aimed at the left wingtip vortex (note: shown mirrored horizontally in figure 1). Analyses were performed in Davis 8.3 (LaVision GmbH, Göttingen, Germany), with a sum of correlation routine on a single image pair, using final box size 24 px \times 24 px with 50% overlap. The resolved flow field had a resolution of 6 vectors/cm for gliding and 3 vectors/cm for the flapping flight setup. On-wing experiments were performed while the bird was gliding. We used the same PIV system as above, but with the field of view parallel to the sagittal plane. The laser sheet was projected from downstream of the bird at a shallow angle from above with respect to the wind tunnel axis. The cameras were positioned on the opposite side of the bird to the wing studied, making a shallow angle with the wing surface. The images were analysed using 16 px \times 16 px boxes with 50% overlap generating a vector resolution of 13.3 vectors/cm.

Ethics The study was performed in accordance with approved experimental guidelines. Procedures were approved by the Malmö-Lund animal ethics committee (M 33-13).

Data Accessibility The vector data shown in figure 1 have been uploaded in tab-separated format as Electronic Supplementary Material.

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Authors' contributions MK and LCJ conceived the study; MK trained the bird; MK and LCJ carried out the experiments; MK, LCJ and AH drafted the manuscript

Competing interests We have no competing interests

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