Flow Features of the Near Wake of the Australian Boobook Owl (Ninox boobook) During Flapping Flight Suggest an Aerodynamic Mechanism of Sound Suppression for Stealthy Flight

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Synopsis The mechanisms associated with the ability of owls to fly silently have been the subject of scientific interest for many decades and may be relevant to bio-inspired design to reduce noise of flapping and non-flapping flying devices. Here, we characterize the near wake dynamics and the associated flow structures produced during flight of the Australian boobook owl (Ninox boobook). Three individual owls were flown at 8 m s⁻¹ in a climatic avian wind tunnel. The velocity field in the wake was sampled at 500 Hz using long-duration high-speed particle image velocimetry (PIV) while the wing kinematics were imaged simultaneously using high speed video. The time series of velocity maps that were acquired over several consecutive wingbeat cycles enabled us to characterize the wake patterns and to associate them with the phases of the wingbeat cycle. We found that the owl wake was dramatically different from other birds measured under the same flow conditions (i.e., western sandpiper, Calidris mauri and European starling, Sturnus vulgaris). The near wake of the owl did not exhibit any apparent shedding of organized vortices. Instead, a more chaotic wake pattern was observed, in which the characteristic scales of vorticity (associated with turbulence) are substantially smaller in comparison to other birds. Estimating the pressure field developed in the wake shows that owls reduce the pressure Hessian (i.e., the pressure distribution) to approximately zero. We hypothesize that owls manipulate the near wake to suppress the aeroacoustic signal by controlling the size of vortices generated in the wake, which are associated with noise reduction through suppression of the pressure field. Understanding how specialized feather structures, wing morphology, or flight kinematics of owls contribute to this effect remains a challenge for additional study.
Introduction

Owls are exceptional hunters due to the fact that most species of the order Strigiformes share the common characteristic of flight which is nearly inaudible to humans and, more importantly, to their prey (Mascha 1904; Dubois 1924; Neuhaus et al. 1973; Bachmann et al. 2007; Sarradj et al. 2011). Owl’s stealth mechanisms (Thorpe and Griffin 1962) function during both flapping and gliding flight modes. There are many potential contributors to this specialized feature of the owls such as wing morphology, unique feathers structures, and flight behavior (Graham 1934). Their typical gliding Reynolds numbers are within the intermediate range \([O(10^5)]\), therefore, low Reynolds number theories (Weis-Fogh 1973) cannot predict their unique flight pattern. In addition, owls feature highly maneuverable low-speed gliding flight capabilities (Johnsgard 1988), yet their aerodynamic performance (lift–drag ratio) has been suggested to be relatively low (Kroeger et al. 1972; Geyer et al. 2017).

The most extensive area of research has been focused on the role of the feathers (Graham, 1934); both on their material properties including flexibility as well as their geometrical ones such as location and spacing. The material property most studied is the velvety surface of the flight feathers. Graham (1934) observed that these velvety feathers (sometimes referred to as downy) feature long hairs and barbules, which he hypothesized would muffle any rustling noise associated with feathers rubbing together. He also suggested that these feathers act as a sound absorber, which would dampen out any small vibrations near the wing. Studies modeling the velvety feathers with an artificial surface that mimics the feathers (e.g., velvet) have shown that the separation bubble is reduced, delayed, or eliminated altogether (Klänn et al. 2009, 2012; Winzen et al. 2013). Winzen et al. (2015a, 2015b) showed that the velvety feathers as well as the flexibility of the wing stabilize the flow field at low Reynolds numbers, enabling the owl to fly more slowly.

Another unusual aspect of the owl wing is the leading-edge serrations: a comb of evenly-spaced bars along the wing leading-edge. Graham (1934) emphasized the importance of the leading-edge serrations as a major noise reducer. Commonly, the flow past the leading-edge over the wing surface may be separated depending on the wing’s angle of attack and its camber. These serrations have been found to stabilize the flow (Winzen et al. 2014) and promote the development of a leading-edge vortex (LEV) (Lawson and Riley 1995) that can augment lift (Geyer et al. 2017). Kroeger et al. (1972) and Anderson (1973) suggested a mechanism to achieve this that involved redirecting the flow passing through the serrations toward the wingtip, which they proposed delays flow separation and produces non-linear lift on the outer half of the wing. Rao et al. (2017) demonstrated that leading-edge serrations play a crucial role in sound suppression at the expense of low aerodynamic performance at low angles of attack.

The fringes along the trailing-edge of the wing have also been studied in connection with the silent flight of owls. Once the flow passes the wing, it is shed from the trailing-edge toward the wake region. Former studies show that these fringes can manipulate the aerodynamic noise (Bachmann et al. 2012; Geyer et al. 2012; Jaworski and Peake 2013). Geyer et al. (2012) conducted acoustic wind tunnel experiments on prepared wings from a variety of bird species and concluded that the silent flight of owls is a consequence of their special wing and feather adaptations.

Relative to the role of feathers (Wagner et al. 2017; Weger and Wagner 2017), investigations of
the wake characteristics, and their relation to quantities like pressure that influence noise generation, are sparse. In particular, wake measurements of freely flying owls that account for all of the aforementioned feather features, along with flying behavior, are lacking. The wake signature provides information on flight performance (i.e., aerodynamic forces) and sheds light on the wing–wake interaction and associated flow mechanisms (Chin and Lentink 2016).

The distribution of the pressure field in the wake results from its flow dynamics. The differential form of the momentum equations (Navier–Stokes) describes the coupling between the pressure and the velocity fields. The formation of the wake flow region stems from the two shear layers moving across the airfoils and interacting beyond it. The velocity field in the near wake region is governed by a streamwise velocity deficit that is formed from the merger of the two-shear layers. The velocity deficit indicates high level of shear in the wake region, as well as vorticity. When the Reynolds number is relatively high, the wake becomes turbulent and vorticity plays a major role in the flow dynamics.

Since the pressure is coupled with velocity, it is also coupled with velocity gradients. It is sometimes convenient to express the pressure as a function of the velocity field by taking the divergence of the Navier–Stokes equation and applying the continuity equation. This results in an expression that is similar to the Poisson equation (Corcos 1964). Re-arranging the equation can yield an expression for the pressure as a function of vorticity and strain, known as the pressure Hessian. The noise generated in the wake, which is commonly referred to as aerodynamic noise (or aeroacoustics), is a function of the velocity field and its nature (Lighthill 1952, 1954). The sound waves are essentially pressure waves and the aerodynamic noise is governed by the pressure distribution within the flow. Pressure and density perturbations generate pressure waves which are correlated with the sound waves. Since pressure and velocity are coupled, in order to characterize the aeroacoustics signature of the owl, one needs to study the wake dynamics.

Advances in technology have allowed for quantitative measurements of wakes using particle image velocimetry (PIV). This method has been applied to a number of flying species (i.e., Spedding et al. 2003; Hedenström et al. 2006; Rosén et al. 2007; Henningsson et al. 2008; Johansson and Hedenström 2009; Tobalske et al. 2009; Altshuler et al. 2009; Hubel et al. 2010; Muijres et al. 2012; Kirchhefer et al. 2013; Gurka et al. 2017), and measurements have been made in both the far wake (Spedding et al. 2003; Hedenström et al. 2006; Rosén et al. 2007; Henningsson et al. 2008; Johansson and Hedenström 2009; Tobalske et al. 2009; Altshuler et al. 2009; Hubel et al. 2010; Muijres et al. 2012) and near wake (Kirchhefer et al. 2013; Gurka et al. 2017). All former wake studies of birds have demonstrated organized shedding in the wake during flapping flight (see details of their data collection and the specimens tested in Supplementary 1). The organized pattern in the wake of flapping birds wing is dominated by the shear layers generated above and below the wing, coupled with root and tip vortices that merge into the wake region, branching a set of vortex lines that dominate the wake. The organized shedding enables estimation of aerodynamic forces, such as lift where Kutta–Joukowski theorem can be applied to estimate it during flight (Henningsson and Hedenström 2011). These unique measurements in the wake of freely flying birds are both difficult to obtain and imperative to the advancement of our understanding of the different specialized characteristics of various bird species. They provide critical insight needed to compare to theoretical models and visualizations of the wake dynamics of flying birds (i.e., Rayner 1979a, 1979b). It is noteworthy to mention that these conceptual models (Rayner and Gordon 1998) assume that the wake flow exhibits some sort of organized motion and are idealized.

Recently, Doster et al. (2014) flew a trained barn owl (Tyto alba) in a long hallway, where they performed stereo-PIV measurements around the owl during flight. They showed, qualitatively, that a complex vortex flow system was developed in the wake during flapping flight. However, a well-defined topographical characterization of the wake of an owl and a quantitative estimation of the aerodynamic forces exerted on it are lacking, either experimentally or numerically.

In this study, PIV measurements in the near wake of a freely flying boobook owl (Ninox boobook) were performed and the results presented herein provide unique insight into the aerodynamics of owls and the interaction between their unique wing morphology and wake flow dynamics. We compare the wake characterization to two other species that we have measured under the similar conditions: a passerine songbird: European starling (Sturnus vulgaris), and a non-passerine shorebird: western sandpiper (Calidris mauri). We use wing kinematics from video and wake reconstructions from PIV measurements to compute characteristic spatial flow scales of the wakes. We show that the characteristic spatial scales...
of the wake relative to chord size of the owl are smaller than those of the other two species and that the owl exhibits the smallest pressure Hessian. Because the near wake flow affects the pressure field within the wake, and the pressure field is related to the aeroacoustic noise (Lighthill 1952), one can assume that the wake characteristics play a major role in the aeroacoustic variations.

Materials and methods

Birds

Two male and one female captive reared boobook owls (N. boobook) were obtained from the raptor program of the African Lion Safari in Cambridge, Ontario, Canada and brought to the Advanced Facility for Avian Research (AFAR) at the University of Western Ontario, London, Ontario, Canada under animal protocols from the University of Western Ontario Animal Care Committee (UWO #2010-216) and the African Lion Safari (BOP-15-CS). Morphological parameters of the owls, as well as the non-dimensional flow numbers associated with the performed experiments are summarized in Table 1.

Over several days the birds were brought to the AFAR in the morning and flown the same day after a brief acclimation. The owls were handled by a professional trainer (G.M.) but were not systematically trained in advance of experiments. Rather they flew steadily for several seconds on each attempt, long enough to capture image sequences suitable for PIV and kinematic analysis. Although the flights took place during daytime the wind tunnel was dark so that PIV could be performed. Optoisolators operated by six infrared transceivers were integrated into the PIV system (upstream from the laser sheet location) in order to prevent direct contact between the bird and the laser sheet (Kirchhefer et al. 2013). The optoisolators triggered the laser only when the owl was flying upstream from the PIV field of view (FOV). The isolation from the laser sheet and triggering system ensured the safety of the birds.

Wind tunnel

The owls were flown in the hypobaric climatic wind tunnel at the AFAR [see Kirchhefer et al. (2013) for more details]. The wind tunnel is a closed loop type with a glass octagonal test section of 2 m length, 1.5 m width, and 1 m height preceded by a 2.5:1 contraction. The turbulence intensity at the test section was smaller than 0.3% with a velocity profile uniformity of 0.5%. Speed, pressure, temperature, and humidity can be controlled to generate various flight conditions at different altitudes. The birds were introduced into the test section through a 0.5 m open jet section located between the downstream end of the test section and the diffuser. The flight conditions for all the owls were at ground level: atmospheric pressure, a temperature of 15 ºC, and a relative humidity of 80%. The wind tunnel speed during the owls’ flight was set to 8 m/s. Using a projected cross-section of the owl (#1 in Table 1), conservative estimate of the blockage ratio is below 3.5%. We assume that wall effects due to interaction between the wing tip and the wind tunnel wall were negligible given that the minimum gap between the wall and the wing tip was about 40 cm, which is much larger than the flow scales characterized by the wing chord (~13 cm).

Particle image velocimetry

A long-duration time-resolved PIV system (Taylor et al. 2010) was employed to measure the near wake field behind the owls’ wings during flight. A schematic description of the PIV setup and the hypobaric wind tunnel at AFAR are shown in Fig. 1. The PIV system consisted of a 80 W double-head diode-pumped Q-switched Nd:YLF laser operating at a wavelength of 527 nm and two CMOS cameras (Photron FASTCAM-1024PCI) with spatial resolution of 1024×1024 pixel2 operating at a rate of 1000 Hz and a 10 bit dynamic range. The PIV system was capable of continuously acquiring image pairs at 500 Hz using two cameras for up to 20 min. Olive oil particles, 1 μm in size were introduced into the wind tunnel using two Laskin nozzles.

| Owl | Mass (g) | Wing span (cm) | Root chord (cm) | Semi-span (cm) | Body length (cm) | Body width (cm) | Wingbeat frequency (Hz) | Reynolds number | Strouhal number | Reduced frequency |
|-----|---------|----------------|----------------|---------------|-----------------|-----------------|----------------------|----------------|---------------|------------------|
| 1   | 273     | 90             | 13             | 40            | 30              | 10              | 6                    | 66,200         | 0.35          | 0.31             |
| 2   | 300     | 78             | 14             | 34            | 31              | 10              | 6                    | 71,300         | 0.37          | 0.33             |
| 3   | 255     | 70             | 14             | 30            | 31              | 9               | 6                    | 71,300         | 0.37          | 0.33             |
(Echols and Young 1963) at the downstream end of the test section; thus, it did not cause a disturbance to the flow or to the bird.

One of the CMOS cameras was used for the PIV, while the other CMOS camera was used for measuring the wingbeat kinematics simultaneously with the PIV. The PIV camera’s FOV was $13 \times 13 \, \text{cm}^2$ corresponding to $1c \times 1c$, where $c$ is the owl mean chord length (an average of the three owls’ chord lengths) and the kinematic camera’s FOV was $52 \times 52 \, \text{cm}^2$ corresponding to $4c \times 4c$, as shown in Fig. 2. The near wake flow field was sampled in the streamwise-normal plane with temporal resolution of 500 Hz and the distance from the owl’s trailing-edge to the FOV varied between 1.4 and 4 chord lengths. Multiple experiments were conducted to sample the near wake flow field at different locations along the wing span of the owl, which enabled us to comparatively analyze the wake characteristics developed at different wing sections along the span at each section.
wingbeat. The velocity fields were computed using OpenPIV (Taylor et al. 2010) with 32 x 32 pixel\(^2\) interrogation windows and 50% overlap, yielding a spatial resolution of 64 vectors per average chord, equal to 1.8 vectors per mm. The average pixel displacement was about 6 where the time between two exposures was set to 90 \(\mu s\). The coordinate system used is a right-handed Cartesian system, where \(x\), \(y\), and \(z\) corresponds to the streamwise, normal, and spanwise directions. \(x\) is directed downstream, \(y\) is directed upward, and \(z\) is determined according to the right-hand rule. The streamwise and normal velocity components are denoted by \(u\) and \(v\), respectively.

| Owl | Experiment number | Scene number | Number of vector maps | Total number of identified wakes | PIV downstream location (\(c\)) | Light sheet location |
|-----|-------------------|--------------|-----------------------|-------------------------------|---------------------------------|---------------------|
| 2   | 1                 | 135          | 318                   | 150                           | 3.8                             | Between the primary and secondary remiges |
| 2   | 2                 | 136          | 304                   | 100                           | 2.1                             | Between the primary and secondary remiges |
| 3   | 3                 | 137          | 480                   | 125                           | 2.4                             | Center of the primary remiges |
| 3   | 4                 | 141          | 271                   | 100                           | 1.6                             | Between the primary and secondary remiges |
| 1   | 5                 | 146          | 410                   | 100                           | 3.3                             | At the tip of the primary remiges |
| 3   | 6                 | 150          | 150                   | 120                           | 2.9                             | Close to the root at the secondary remiges |
| 1   | 7                 | 153          | 770                   | 100                           | 4.2                             | At the tip of the primary remiges |
| 1   | 8                 | 158          | 912                   | 195                           | 3.9                             | At the tip of the primary remiges |
| 1   | 9                 | 159          | 813                   | 250                           | 2.1                             | Between the primary and secondary remiges |

\(a\)Indicate the number of maps where both wing kinematics and flow field were successfully analyzed out of the total number of vector maps per experiment.

\(b\)The distance from the trailing edge where the wake was captured.

\(c\)With respect to the wing spanwise location.

Estimation of owl wing kinematics

Wingbeat kinematics were recorded using one of the high-speed CMOS cameras as described above. From the acquired images, we calculated the wingbeat frequency, wingbeat amplitude, and angle of attack. The kinematic images were synchronized with the PIV images in order to provide a direct relationship between the wake formed by the wing motion and its kinematics.

The wake locations with respect to the trailing-edge of the wing during flight were determined from both captured images and the distance between them as depicted in Fig. 2. To determine the location of the light sheet along the bird’s wing or body, a 30 Hz CCD camera with 1600 x 1200 pixel\(^2\) resolution was mounted downstream of the test section pointing toward the location where the bird would trigger the laser and taking spanwise-normal plane images. A spatial calibration was performed before the experiment. Once synchronized, spanwise positions were assigned to the wake data acquired at 500 Hz based on interpolation from the simultaneously recorded spanwise positions. These images enabled us to identify the location of the light sheet relative to the wing during the experiments and determine its location with respect to the body center. This information allowed us to couple the wake flow features with the wing morphology: wingtip, primary and secondary remiges, and close to the body (at the root).

We extracted the wingtip motion using motion analysis software, Kinovea (https://www.kinovea.org). A point close to the wingtip was tracked for all owls over the continuous wingbeat cycles. For each data set, the tracking identification for the kinematics analysis was located at the tip of the primary feather eight (P8, the third wing feather from the distal end of the wing). The number of wingbeat cycles was calculated by normalizing the total evaluation time with the wingbeat period.

Flow experiments

Table 2 summarizes the collected PIV data sets obtained during the experiments for the three owls that were analyzed in this study. Only successful owl flights were recorded. A successful flight refers to an experiment where the owl triggered the laser and the PIV system acquired images of the flow field simultaneously with the wing kinematics. The data presented herein correspond to sets (“scenes”) where the owl did not accelerate or decelerate and maintained altitude during flapping mode. A total of nine scenes are presented, where each scene consists of hundreds of vector maps that correspond to multiple consecutive wingbeat cycles during free flight. This large set of data enabled us to statistically
characterize the near wake flow field and its interaction with the owl’s wing. The PIV measurements were taken behind the owl’s wing where a wake was present, and the wing motion was clearly identified in the kinematic images.

An error analysis based on the root sum of squares method was applied to the velocity data and the wing kinematics, following Gurka et al. (2017). The errors were estimated as: 2.5% for the instantaneous velocity values, 10% for the instantaneous vorticity, and 4% for the circulation, which was calculated, based on the vorticity field (Raffel et al. 2007). The error introduced in the kinematic analysis resulted from the spatial resolution of the image and the lens distortion leading to an estimated error of 5% in the wing displacements.

Blob analysis
In order to characterize the differences within the wake flow patterns of the birds studied herein, a quantitative comparison based on patterns topography was performed. For the topographical analysis, we utilize the so-called “blob” analysis. The motivation of this analysis is to characterize the dominant spatial scales in the reconstructed wake. The vorticity contours are presented in Fig. 5a here, and in Figs. 4 and 5 in Gurka et al. (2017). All the contours plotted employ a threshold of −1 and +1 for the normalized vorticity. The blob analysis essentially calculates the area of the concentrated vorticity regions (\(\omega_xU_\infty < -1\) and \(\omega_xU_\infty > 1\)) and computes a histogram of these areas. A more detailed description of the procedure can be found in the Supplementary Material, Supplementary 3. For brevity, the analysis transformed vorticity contour images to grayscale images and removed the background. The grayscale image was filtered and then converted into a binary image. The binary image was evaluated for interconnectivity of non-zero pixels using a connectivity of eight nodes. The sums of the connected pixels were used to compute an area along with the image calibration from the PIV measurements. The histogram of these areas was plotted and power density functions were fit to the histograms as further described in the wake topography characterization subsection.

Flow scale analysis
In order to characterize the scales of the flow in the near wake region and their dependency on the flapping wing motion we choose to utilize a known statistical approach when estimating the integral lengthscale in case of turbulent flow (Pope 2000).

In order to estimate the fluctuating part of the flow, we applied a local Galilean decomposition; i.e., \(u' = u - u_{\text{avg}}, v' = v - v_{\text{avg}}\) where \(u_{\text{avg}}\) and \(v_{\text{avg}}\) are the spatially averaged (over the PIV FOV) velocities of the velocity components examined over the direction of the correlation. A similar technique was applied to PIV data in shear flows to remove the convection velocity (Adrian et al. 2000). The analysis does not attempt to estimate turbulent properties based on this decomposition; but rather is used to calculate the auto-correlation values for a fluctuating portion of the velocity field, which presumably is associated with turbulence. The longitudinal scale corresponds to the result obtained from correlating the velocity component along the same direction and calculating the area under the normalized correlation curve. Correlating the velocity components along the normal direction yields the transverse scales.

Pressure Hessian
The pressure Hessian is a key quantity that controls vortex stretching through interactions associated with the pressure term (Ohkitani and Kishiba 1995; Tsinober 2013) in the momentum equations for fluids. The pressure Hessian is computed by applying a divergence to the incompressible Navier–Stokes equations:

\[
\nabla^2 p = \rho \left( \frac{1}{2} \omega^2 - s^2 \right),
\]

where \(p\) is the pressure, \(\omega^2 = \omega_x\omega_x\) \(s^2 = s_x^2\) \(\omega_x\) is the vorticity vector, \(s_x\) is the strain rate tensor, and \(\rho\) is the fluid density. Note that because the data are comprised from two-dimensional flow field measurements, we can only estimate the corresponding terms contributing to the pressure Hessian. We account for the spanwise vorticity component and the rate of strains in the streamwise and normal directions. While this term provides an insight to the relation between vorticity and strain, it also provides an indirect estimate of the pressure field developed within the flow.

Results
Owl wing kinematics
We use a similar approach as Gurka et al. (2017), which followed guidelines suggested by Wies-Fogh (1973), where the wingbeat cycle was divided into four distinct phases: upstroke (US), transition from US to downstroke (USDS), DS, and transition from DS to US (DSUS). Following an analysis of the owl wing’s kinematics as described in the “Materials and methods” section, Fig. 3 presents images in
sequential order from right to left as an owl flies through one full wingbeat cycle during forward flight (upstream, against the wind). We estimated that for the various flight durations, the average frequency was about 6 Hz (Fig. 4). Therefore, the corresponding Strouhal number for owls #2 and #3 was 0.37 and for owl #1 was 0.35. Herein, the Strouhal number is defined as \( St = \frac{fA}{U_{\infty}} \), where \( f \) is the flapping frequency, \( U_{\infty} \) is the speed of flight (wind tunnel speed), and \( A \) is the peak-to-peak cross stream amplitude of the motion (Anderson et al. 1998). These values suggest that the owls' wings, according to Anderson et al. (1998), may generate leading edge vortices during flapping flight. A semi-sinusoidal pattern is observed, covering the US, DS, and transition phases over almost two consecutive wingbeat cycles. The axes presented are normalized by the chord length. The trend is similar for various data sets covering flights of the three owls. The solid vertical lines define the transitions between the wingbeat phases whereas the dashed line illustrates the point during the DS phase where the angle of attack was calculated. It is assumed that during the flight, the owl wing operates at relatively high angles of attack, which is common in other birds as well (Shyy et al. 2008). Operating at high angles of attack at their characteristic Strouhal numbers allows owls to fly more slowly while still being able to generate lift (Rosti et al. 2017) through the formation of LEV (Anderson 1973).
Fig. 5 Near-wake flow features of the boobook owl while flying in a flapping mode. The owl flew from right to left. (i) Wake reconstruction—the wake was sampled behind the wing at different spanwise sections: a) between the primary and secondary remiges; Experiment #9, b) outer region of the wing; the furthest location in the primary remiges; Experiment #8 and c) Middle of the primary remiges; Experiment #3. Contours represent the values of spanwise vorticity and the velocity vectors superimposed on the contour maps depict the two-dimensional, two-component velocity field in the near wake. The regions of positive and negative vorticity are marked in red and blue, respectively. The spanwise vorticity was normalized by the ratio between the chord length $c$, measured at the semi-span location (between the primary and secondary remiges) and the free-stream velocity (i.e., the flight speed), $U_\infty$. (ii) Wingtip displacement—the wingtip displacement is plotted against downstream chord length to directly correlate with the respective wake. The vertical black lines in each graph represent the transition from US to DS or DS to US, respectively. All the wakes have been calculated based on the same threshold of the normalized vorticity values ($-1$ to $+1$).
Near wake fluid dynamics

The near wake of the owl provides insight into the flow–owl interaction. The owl wakes differ qualitatively from those of other birds that have been measured (by us and others), which are more similar to each other. In order to qualitatively assess the wake evolution resulting from the owl in flapping flight, we followed the same procedure as originally suggested by Spedding et al. (2003) and utilized later for other passerines and shorebirds (Kirchhefer et al. 2013; Gurka et al. 2014). The wake evolution in time, which can be transformed into the evolution in space enables one to observe how the vortical patterns in the wake region provide a unique signature of a bird’s flight. The wake reconstruction procedure we used is described in detail in Gurka et al. (2014). Throughout the presented wingbeat cycles, the owls’ position did not change much relative to the measurement plane. Therefore, Taylor’s hypothesis (1938) is applied, following the assumption that the flow remains relatively unchanged as it passes through the measurement plane. The utilization of the long-duration time-resolved PIV system enabled the reconstruction of the wake evolving behind the wings. The owls flew from right to left (Fig. 3); therefore, the downstream distance is measured as positive chord lengths. What appears as downstream essentially happened earlier while what appears as upstream happened later. Each wingbeat cycle corresponds to five to eight chord lengths for the various wakes analyzed. Each individual scene analysis corresponds to 0.5–2 wingbeat cycles; thus, we can analyze the flow field behind the owl continuously and identify trends within the flow patterns.

The evolution of the near flow wake behind the freely flying owls is depicted in Fig. 5. It appears that the shedding of vortices from the wing are somewhat lacking coherence or consistency where one would expect to observe some sort of shedding behavior; organized or non-organized from a propulsive wake (as can be observed during birds’ flight, i.e., Spedding et al. 2003; Hedenström et al. 2006; Rosén et al. 2007; Henningsson et al. 2008; Johansson and Hedenström 2009; Tobalske et al. 2009; Altschuler et al. 2009; Hubel et al. 2010; Muijres et al. 2012; Kirchhefer et al. 2013; Gurka et al. 2017). The vorticity patterns in the wake appears disorganized, as shown in multiple sets of the data for the three owls investigated (Fig. 5). Figure 5a depicts the wake reconstruction from data taken in Experiment 9. The wake presented corresponds to the flow formed above and below the wing section, located between the primary and secondary remiges. Additional datasets acquired at the same location are shown in the Supplementary Material for Experiments 1, 2, 4, and 7 (see Supplementary 2). Experiment 8, presented in Fig. 5b, corresponds to the wake formed at the outer region of the wing; the furthest location in the primary remiges, where a tip vortex is present. The tip vortex appears as a concentrated spanwise vorticity region, almost circular in its geometrical shape marked with strong positive and negative vorticity values preceded by weak shedding that occurs over the entire wingbeat cycle. Additional datasets acquired at the same location are shown in the Supplementary Material for Experiments 5 and 7 (see Supplementary 2). It is noteworthy that Experiment 7 had mixed wake flow patterns, which may indicate that the owl was moving in the spanwise direction during flight. Figure 5c depicts the wake behind the middle point of the primary remiges (Experiment 3). Experiment 6, which presents the wake behind the secondary remiges close to the root, is depicted in the Supplementary Material (Supplementary 2). In general, the common feature for all the wakes examined is that the concentrated regions of spanwise vorticity are small, suggesting that small scales dominate the wake flow. This qualitative examination of the reconstructed wakes shows a different topography of the vorticity field in comparison to other birds that have been tested in the same facility (Gurka et al. 2017): the near wake flow of passerine such as European starling (S. vulgaris) and America robin (Turdus migratorius) and a shorebird (western sandpiper, C. mauroi) exhibit an organized wake where shedding is observed, although these birds are of different size and flight behavior. Furthermore, bird wakes studied in different facilities over the years have demonstrated organized wakes where shedding was observed independent of the flight mode or the bird species (see Supplementary 1). This discrepancy suggests that owls generate a wake substantially different when compared with these other birds.

Wake topography characterization

In order to quantitatively characterize differences between the wakes of the boobook owl measured in our experiment and those typical of other birds, we performed a topographical and flow-scale analysis of the reconstructed wakes of the boobook owl, European starling, and western sandpiper as described in the “Materials and methods” section. We chose these two birds for comparison because they were flown at the same facility using the same measurement tools, and we have full access to their data. The results of the analysis of each species are
compared and contrasted to enable a measure of the
distinction of the wakes. Figure 6 depicts the histo-
gram for Experiment 9 with the owl, along with the
corresponding histograms for the starling and sand-
piper wakes. The two subplots represent the histo-
grams for the identified areas with positive vorticity
(top figure) and the areas associated with negative
vorticity (bottom figure). The histogram distribution
for the starling and sandpiper appears to be similar,
spanning a range of areas (0.2 × 10⁻⁴ to
2.0 × 10⁻⁴ m²), with a large standard deviation. In
comparison, the owl histogram is more narrowly dis-
tributed with a lower mean area than the other birds.
These results are consistent over the range of experi-
ments presented here (see Supplementary 2). The
measured mean and standard deviation of the blob
analysis histograms of the owl are smaller than the
other two birds and are provided in Supplementary
Table S1 in Supplementary 3. These results
demonstrate that regions of large magnitude vorticity
(ωzdU∞ >|I|) in the wake of the owl tend to be
smaller than those of other birds relative to their
chord size. The limited large-scale motion in the
owl’s wake suggests that large-scale motion may be
suppressed/damped or not generated at all. This re-
sult is also consistent with the qualitative compari-
son of the wakes (Fig. 5a), where the wake
reconstruction of the owl appears to exhibit a disor-
ganized shedding compared with the starling and sandpiper.

Flow scale analysis
For the flow scale analysis, we estimated a character-
istic flow scale using auto-correlation functions ap-
plied to the data in the near wake region (see details
of the birds investigated in Table 3). The flow in the
wake was unsteady and turbulent due to the inter-
mediate Reynolds number. Smith et al. (1993)

Fig. 6 Histogram of the number of concentrated spanwise vorticity regions at the wake of the three birds. The histogram is based on
blob analysis performed on the wake reconstruction contours appear in Fig. 5a for the owl and in Figs. 4 and 5 in Gurka et al. (2017)
for the sandpiper and starling, respectively. The top figures illustrate the positive spanwise vorticity selections and the bottom showing
the negative ones. The left figures compare the owl with the sandpiper; the middle compare it with the starling and the right figures
compare the sandpiper with the starling.
showed a linear relationship between concentrated regions of high vorticity and turbulent flow scales in homogenous turbulence (Smith et al. 1993). The characteristic turbulent scale is known as the integral lengthscale which is calculated from the auto-correlation function of the fluctuating velocity field with respect to a prescribed direction (Pope 2000). The wake developed behind the freely flying owl was unsteady and one cannot use the classical Reynolds decomposition in order to extract the velocity fluctuations. Therefore, we used Galilean decomposition of the velocity field as described in the “Materials and methods” section. Both longitudinal and transverse scales were calculated for the two velocity components and compared between the three birds, as shown in Table 4. The scales presented are averaged over each vector map and then over time: $L_{11}$ is the longitudinal length scale for the streamwise velocity ($u$) in the streamwise direction ($x$) and $L_{22}$ is the longitudinal length scale for the normal velocity ($v$) in the normal direction ($y$). The transverse scales ($L_{12}$ and $L_{21}$) correspond to the flow scales based on the streamwise velocity ($u$) and the normal velocity ($v$) along directions normal to each velocity component, respectively. Because the wake flow results from the wingbeat motion, the flow scales were estimated for two phases during the wingbeat cycle: the transition from DS to US (DSUS) and the transition from US to DS (USDS). The computed scales are normalized by the respective chord lengths (Table 4). The flow scales of the owl wake are smaller by an order of magnitude with respect to the wakes of the other two birds, whereas the flow scales of the wakes behind the starling and the sandpiper have similar magnitude. The flow scales do not seem to be dependent on the wingbeat phases. In addition, these flow scales are substantially smaller than the wing chord length and presumably are governed mainly by vorticity and/or strain. The smaller dominant flow scale found for the owl in comparison to the other birds is consistent with the results of the topographical analysis. The results of the flow scales and topographical analysis quantitatively demonstrate how the owl’s wake is fundamentally different from the two other birds.

Table 3  Morphological characteristics of the birds flown and the experimental parameters used for the fluid dynamic comparative analysis

|             | Mass (g) | Wingspan (cm) | Wing chord (cm) | Wingbeat frequency (Hz) | Wind speed (m/s) | Reynolds number | Strouhal number | Reduced frequency |
|-------------|----------|---------------|-----------------|----------------------|-----------------|----------------|-----------------|------------------|
| Owl         | 273      | 90            | 13              | 6                    | 8               | 66,200         | 0.35            | 0.31             |
| Sandpiper   | 30.3     | 25.5          | 4.5             | 13                   | 10              | 31,000         | 0.28            | 0.19             |
| Starling    | 78       | 38.2          | 6               | 12.5                 | 13.5            | 54,000         | 0.16            | 0.17             |

Table 4  Characteristic flow scales at the near wake based on the auto-correlation of the velocity fields

| Flow scale       | Sandpiper | Starling | Owl |
|------------------|-----------|----------|-----|
| Longitudinal scale | $L_{11}$ | $L_{22}$ | $L_{11}$ | $L_{22}$ | $L_{11}$ | $L_{22}$ |
| DSUS             | 0.19      | 0.26     | 0.14 | 0.18      | 0.11 | 0.07 |
| USDS             | 0.24      | 0.13     | 0.16 | 0.13      | 0.11 | 0.08 |
| DSUS             | 0.15      | 0.18     | 0.14 | 0.11      | 0.06 | 0.09 |
| USDS             | 0.06      | 0.07     | 0.06 | 0.08      | 0.06 | 0.09 |

Note: The scales are normalized by the respective wing chord length.
| DSUS, DS to US phase. |
| USDS, US to DS phase. |

*1 and 2 refers to the streamwise and normal directions in the wind tunnel, respectively.

Pressure distribution within the near wake
To further explore the observed scale reduction, we examined the velocity gradient tensors; mainly the vorticity and strain in the wake region. We use the relation between pressure and velocity gradients through the pressure Hessian [see Equation (1)] that is derived from Navier–Stokes equations and play a dominant role in the vorticity equation, allowing to study the relation between pressure and velocity gradients, locally (Ohkitani and Kishiba 1995; Tsinober 2013). While this term provides an insight to the relation between vorticity and strain, it also provides an indirect estimate of the pressure field developed within the flow. Because aerodynamic noise is associated with pressure, it seems appropriate to examine the pressure Hessian, and compare it with that of other birds whose aeroacoustic signature is louder than that of an owl. Figure 7 presents a histogram distribution of the right-hand side of Equation (1) for the three birds, using the same data as the topographical and flow analyses. The right-hand side term of Equation (1) is calculated at the near wake region behind the wings, for all three birds in flapping mode about the wing mid-section. Therefore, it is plausible to assume that the locations of the measurements with respect to the
wings in the spanwise and streamwise directions were similar and the phenomena observed occurred roughly at the same flow configuration. The blue colored histogram distribution in Fig. 7 corresponds to dataset obtained from Experiment 9 (owl 1), which has a mean value near zero with a tail ranging up to $0.25 \text{ kg/m}^3 \text{s}^2$. In contrast, for the starling, it ranges from 0 to $2.5 \text{ kg/m}^3 \text{s}^2$ (red histogram) and the sandpiper ranges from 0 to $0.5 \text{ kg/m}^3 \text{s}^2$ (green histogram); both with non-zero mean values. The histogram distribution for the starling is flatter, spans a wide range of values, and is similar to a normal distribution while the other two birds have a more skewed distribution, similar to log-normal distributions.

The difference between the distributions may be attributed to the wake flow patterns, which appear to be meandering for the owl and the sandpiper and less meandering for the starling, for the data cases studied herein. It is noteworthy that the same calculation was performed for the other owls’ datasets and all had similar distributions to the one presented in Fig. 7 (blue color histogram) with a similar range of values (see Supplementary Fig. S2 in Supplementary 2). Calculating 95% confidence intervals indicates that there is no overlap in the mean gradient pressure distributions among the owl ($m \pm SD = -0.018 \pm 0.032$, 95% CI $-0.022$ to $-0.013$), sandpiper ($m \pm SD = -0.14 \pm 0.16$, 95% CI $-0.17$ to $-0.12$), and the starling ($m \pm SD = -1.14 \pm 0.43$, 95% CI $-1.21$ to $-1.08$), where $m$ is the mean, SD is the standard deviation, and CI is the confidence interval. These statistics show that the distribution of the pressure gradient of the owl’s wake is closer to zero (at least an order of magnitude smaller compared with the other birds) with little variation. This result indicates that the wake dynamics behind the owl are fundamentally different in comparison to the other two birds—consistent with the results of the other analyses. For the starling and sandpiper, the histogram mean values [right side of Equation (1)] are negative, on average. Here, $\omega^2$ corresponds to enstrophy and $s^2$ is proportional to dissipation; thus, these results imply that dissipation is more dominant in the starling and sandpiper wakes behind the wing mid-span location, relative to the enstrophy [based on the relations between them in Equation (1)]. Yet, for the owl, the enstrophy is approximately double the dissipation as both terms counter each other to yield values in the wake that are close to zero. Therefore, we hypothesize that the owl, using its unique wing morphology, generates more vorticity than strain, which essentially is achieved by generating more small scales while destroying, or not generating, large scales in its wake.

**Discussion**

The near wake flow dynamics of an owl feature unique characteristics that may be associated with its ability to fly silently. Our findings demonstrate significant differences between the wake of an owl and the wake of other birds (Spedding et al. 2003; Hedenström et al. 2006; Rosén et al. 2007;
Henningsson et al. 2008; Johansson and Hedenström 2009; Tobalske et al. 2009; Altshuler et al. 2009; Hubel et al. 2010; Muijres et al. 2012; Kirchefer et al. 2013; Gurka et al. 2017); these include bird wakes studied in various facilities over many years that have demonstrated organized wakes where shedding was observed independent of the flight mode or the bird species (see Supplementary 1).

The qualitative examination of the reconstructed wakes shows a different topography of the vorticity field in comparison to other birds that have been tested in the AFAR wind tunnel (Gurka et al. 2017): the near wake flow of passerines such as European starling (S. vulgaris) and America robin (T. migratorius), and a shorebird (western sandpiper, C. mauri) exhibit an organized wake where shedding is observed, although these birds are of different size and flight behavior. A detailed comparison between the owl wake and two birds: the western sandpiper and European starling were performed. While they are not comparable in size with the owl, they present broadly similar wake patterns although they differ in their flight behavior: long distance migratory, continuous flapping (sandpiper), and intermediate distance migratory, flap-gliding (starling).

In comparison to the other two birds, the wake of the owls is quantitatively different in terms of the scales of the flow. This result was confirmed by two different methods of estimation of the flow scales. The topographical analysis demonstrated that the owl’s wake is qualitatively more disorganized (no street is apparent) at the mid-span location of the wing and contain smaller areas of large magnitude of vorticity ($|\omega_z U_e| > 1$). This result is consistent with the notion that owls do not feature high aerodynamic performance (Kroeger et al. 1972; Geyer et al. 2017). An aerodynamic body is expected to generate an organized street in the wake (Gerrard 1966; Roshko 1993). Yet, such organized structures are absent in the owl’s wake. Furthermore, the flow scale analysis, which estimates the decorrelation scale of the flow patterns in the wake, indicates a smaller scale for the owl compared with the other two birds, consistent with the topographical analysis. The apparent absence of large flow scales may suggest that the turbulence production activity associated with these scales is somewhat limited (Pope 2000; Tsinober 2013). The dominance of small scales in the wake region also indicates an increase in the turbulence dissipation rate and vorticity. Together, this implies that over the wingbeat cycle, there is an imbalance between the production and dissipation of turbulence energy.

The aspects of the flow that result in the different distribution of scales were examined via the distribution of the two-dimensional pressure Hessian in the wake. The distribution for the owl shows that the pressure Hessian term has a mean near zero with a narrow distribution compared with the other two birds. The larger enstrophy in the owl’s wake relative to the dissipation ($\tilde{\gamma}$) further supports the results of smaller flow scales in the wake and/or suppression of larger scales. This result implies that in the owl’s wake the strain and vorticity fields interact with each other differently in comparison to the other two birds because the pressure Hessian describes the non-local interaction between vorticity and strain. The small mean pressure Hessian could be related to the noise suppression because noise and pressure are related, and we conjecture that the suppression of aerodynamic noise occurs through modulation of the flow scales in the wake.

Based on our findings we suggest that most of the owl’s wake has either (i) a strong three-dimensional motion in the spanwise direction (not measured) such that the wake behind the primary remiges is weakened relative to the tip region, or alternatively (ii) experienced a significant degradation of the turbulence level. For the former case it may be that these wake dynamics resulting from flow patterns formed above the wing section are shifted in the spanwise direction toward the wing tip such that the majority of momentum is transferred from the streamwise to the spanwise direction (as suggested originally by Kroeger et al. 1972). This shift would minimize the wake activity behind the majority of the wing by shifting all the momentum toward the tip region.

The degradation of turbulence may be the result of the unique morphological structure of the leading-edge serrations (Bachmann and Wagner 2011), velvety feathers surface, and trailing-edge fringes (Graham 1934) of the owl’s wing. Once the flow interacts with the wing at the leading edge, the serrations funnel the flow and presumably shift some of the momentum toward the tip; then the flow passes over the velvety feathers, forming pseudo-smooth surface; thus, maintaining lift and reducing friction (Bachmann et al. 2007). Subsequently, the flow passes toward the trailing edge. At the trailing edge, some of the fringes are oriented in the
streamwise direction and some are oriented to overlap with the neighboring feathers (Bachmann et al. 2012), generate additional mixing due to their non-structured configuration. We suggest that this process causes the length scales of the flow to decrease dramatically, suppressing the large scales while producing more mixing and forming more small scales, which corresponds to additional generation of vorticity. This additional vorticity and/or suppression of larger flow length scales lead to a decreased pressure gradient field that can be associated with the aerodynamic noise. We suggest that the noise reduction is partially achieved by alternating the scales of the flow. Further research into how the various morphological features of the wings modify flow scales to balance the strain and vorticity fields in such a way that the pressure gradient field is minimized should be pursued.

Ethics

The owls were brought from the “African Lion Safari” in Cambridge, Ontario, Canada under animal protocol number BOP-15-CS and protocol 2010-216 from the University of Western Ontario Animal Care committee.

Data, code, and materials

All relevant data are given within the paper.

Authors’ contributions

H.B.-G. and R.G. were responsible for the design of the experimental setup and performed the experiments and analyzed the data. R.G., J.L., and E.E.H. prepared the manuscript. J.L., H.B.-G., and K.K. performed the data analysis and edited the manuscript. G.A.K. assisted in the setup design and edited the manuscript. C.G. assisted with study design and data collection and edited the manuscript. G.M. was responsible for the capture, care, and training of the experimental birds.

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Supplementary data

Supplementary data available at IOB online.
Synopsis Características do fluxo de esteira proximal da coruja Ninox boobook durante o vôo batido sugerem mecanismo aerodinâmico de supressão sonora para vôo furtivo. Características do fluxo de esteira proximal da coruja Ninox boobook durante o vôo batido sugerem mecanismo aerodinâmico de supressão sonora para vôo furtivo. (Flow features of the near wake of the southern boobook owl (Ninox boobook) during flapping flight suggest an aerodynamic mechanism of sound suppression for stealthy flight).
This makes it possible to create laminar flow patterns and to relate them to the wingbeat cycle. We observed an even more chaotic pattern of vortices compared to other species measured under the same flow conditions (e.g., Swainson’s Thrush, Catharus ustulatus). The boobook’s vortices were not apparent as organized structures. Instead, we observed a more varied pattern of vortices, where the characteristic scales of vorticity (associated with turbulence) were substantially smaller than in other species. The estimation of the pressure field shows that the boobooks reduce the Hessian pressure field (i.e., the pressure distribution) to approximately zero. Our hypothesis is that the boobooks manipulate the flow field to suppress the aeroacoustic signal by controlling the size of the vortices generated in the flow, which are associated with the reduction of noise through the suppression of the pressure field. Understanding how the specialized plumage structures, wing morphology, or flight kinematics contribute to this effect remains a challenge for additional studies.

**Synopsis**

Boobooks (Ninox boobook) have been the subject of scientific interest for many decades and are relevant for bioinspired design to reduce the noise of flapping flight devices. Here, we characterize the near-wake dynamics and flow structures associated with the flight of the Australian boobook (Ninox boobook). Three individual boobooks flew at 8 ms\(^{-1}\) in a wind tunnel. The velocity field in the near-wake was measured at 500 Hz using long-duration high-speed particle image velocimetry (PIV), while the wing kinematics were simultaneously recorded using high-speed video. Time series of velocity maps acquired over several consecutive flapping cycles allow us to characterize the wake patterns and associate them with the flapping phases. We discovered that the boobook’s wake was dramatically different from other species measured under the same flow conditions (e.g., Correlimos of Alaska, Calidris mauri, and the Pintail Shrike, Strunus vulgaris). The boobook’s near-wake did not show any apparent detachment of organized vortices. Instead, we observed a more varied pattern of vortices, where the characteristic scales of vorticity (associated with turbulence) were substantially smaller than in other species. The estimation of the pressure field shows that the boobooks reduce the Hessian pressure field (i.e., the pressure distribution) to approximately zero. Our hypothesis is that the boobooks manipulate the flow field to suppress the aeroacoustic signal by controlling the size of the vortices generated in the flow, which are associated with the reduction of noise through the suppression of the pressure field. Understanding how the specialized plumage structures, wing morphology, or flight kinematics contribute to this effect remains a challenge for additional studies.
Flow features of the Ninox boobook

कलापविरा, कलापविरा कलाप विदुर्दव निकट Ninox boobook विदुर्दव विदुर्दव कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरा कलापविरা
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