A Method for Continuous Study of Soaring and Windhovering Birds

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Abstract

Avian flight continues to inspire aircraft designers. As the scales of autonomous aircraft reduce to those of birds and large insects, new control challenges are apparent when attempting to hold steady flight in turbulent atmospheric wind. Some birds, however, are capable of remarkably stable hovering flight in the same conditions. This work describes the development of a wind tunnel configuration that facilitates the study of flapless windhovering (hanging) and soaring bird flight in wind conditions replicating those in nature. Updrafts were generated by flow over replica “hills” and turbulence was introduced through upstream grids. Successful flight tests with windhovering nankeen kestrels (*Falco cenchroides*) were conducted, verifying that the facility is suitable for future studies investigating the flight of soaring and windhovering birds in smooth and turbulent flows. The wind tunnel allows the flow characteristics to be carefully controlled and measured, providing great advantages over outdoor flight tests. Also, existing wind tunnels may be readily configured using this method, eliminating the need for the development of dedicated bird flight wind tunnels.

1 Introduction

Unmanned air vehicles (UAVs) are challenged to hold steady flight in windy conditions, whereas birds are known to maintain far steadier flight under a range of flight conditions. Several species of birds, including ospreys, kestrels, and pied kingfishers, can hover at low altitudes when flying into the wind, essentially keeping their heads stationary relative to the Earth’s surface as they watch for small prey moving below [1–3]. This flight behaviour is termed *windhovering*. Windhovering without wing flapping, termed *hanging*, can occur when birds are in the presence of suitable orographic updrafts (i.e. hill soaring) [4]. This entails coping with the significant turbulence inherent in the atmospheric boundary layer (ABL) [5]. Kestrels have been observed to hang with their heads deviating from a fixed position by less than 6 mm despite the turbulent nature of the wind [1]. The control mechanisms and sensing strategies used to maintain this stability are not understood. Studies investigating the control strategies employed by windhovering birds would likely discover novel gust-mitigation techniques that inspire the development of ultra-stable UAVs, a concept that has been a research focus of our group [6–12].

Whilst the aerodynamics of windhovering flight has been studied outdoors [4], there have been no studies of windhovering flight in controlled smooth and turbulent wind flows. It is considered that this is due to the lack of a suitable facility which would permit windhovering studies. Tilting wind tunnels have been used to study the gliding flight of a range of birds [13–18], however, these studies focus on aerodynamic performance in smooth flow rather than investigating control responses to gusts and turbulence. Such responses in flapping flight have been the focus of several studies involving hummingbird flight through gusts or turbulence [19–21], however, wing flapping confounds the extraction of the disturbance mitigation control kinematics. Cheney et. al. [22] studied gliding flight of a barn owl through discrete vertical gusts in still air, but this a different situation from soaring and hanging flight in moving air with continuous turbulence which is more representative of fixed-wing flight through atmospheric turbulence. This work describes modifications to a wind tunnel environment to enable soaring and windhovering

flight behaviours of birds to be studied in a range of replicated outdoor conditions. Initial results of flight trials with nankeen kestrels (*Falco cenchroides*) are also described to illustrate the utility of this approach.

1.1 The Windhovering Flow Environment

To replicate the flow conditions in which birds naturally windhover it is necessary to understand several key properties of the flow, including windspeeds, updraft angles and turbulence intensities. The typical flow updraft angle preferred by hanging kestrels can be obtained from the work of Videler and Groenewold [4] where a glide angle between 6 and 7 degrees in flight speeds of 7 to 12 m/s was reported for kestrels windhovering over a dike in the Netherlands. These estimates were obtained by correlating windhover locations to wind profiles constructed from a set of 225 measurements of mean wind speeds and angles over the dike at 13 different heights.

To date, there appear to be no dedicated outdoor flow measurements to document the turbulence in which birds windhover, however, several studies have sought to measure the turbulent wind domains for UAVs flying over similar terrains. One such study was conducted by Watkins et al [23] who utilised a bank of four TFI Cobra Probes mounted on a mast above a stationary and moving car. This documented the flow environment experienced by flight through the atmospheric boundary layer. Probes were laterally displaced by 150 mm giving a “virtual span” of 450 mm. These measurements of fluctuating velocity components included flow in city, suburban and relatively smooth domains. They revealed the detailed time-varying flow characteristics relevant to the flight of birds and UAVs. Details can be found in [24]. This work was extended to encompass a range of probe lateral separations, locations and heights up to 10 m above the ground [25]. Later work involved airborne measurements using the cobra probes [10, 26–27]. Additional hitherto unpublished measurements were taken above sand dunes where birds had been observed to windhover, using the method and instrumentation described by Thompson et al [28] and in the thesis by Thompson [25]. The location was on the north side of the Gower Peninsula in the UK and the upstream fetch was smooth (the Atlantic Ocean and a short section of relatively smooth sand). The longitudinal velocity measurements from the four laterally separated Cobra probes were closely similar, as seen in the measurement sample provided in Fig. 1a. The spectral characteristics of the turbulence show the $-5/3$ Kolmogorov spectral decay, as seen in Fig. 1b, thus confirming the turbulence in the flow was well-mixed and free from any local shedding events from upstream structures. From eight such data sets, very similar turbulence characteristics were found. Longitudinal turbulence intensities ranged from 8–10% in mean wind speeds of 6–10 m/s. Other data sets obtained in rougher mountainous terrains (where birds had again been observed to windhover) exhibited turbulence intensities of typically 15%.

Thus the requirements for the flow characteristics in the wind tunnel were to provide a region of flow sufficiently large for birds to windhover in flow speeds ranging from 7 to 12 m/s, time-averaged flow pitch angles in the range 5 to 8 degrees, and turbulence intensity levels up to 15 %.

2 Methods And Materials

2.1 RMIT Industrial Wind Tunnel

One possibility for studying continuous gliding flight is to have a dedicated wind tunnel that can be inclined to the glide angle of a bird such as those described by Pennycuick, Alerstam and Hedenstrom [29]. However, an alternative is to modify the test section of a conventional tunnel to incorporate a ramp replicating a “hill” and thus generate an updraft in which birds can soar. The RMIT Industrial Wind Tunnel was selected for such a modification since the size of its test section (3 m × 2 m × 9 m) was considered well-suited to study windhovering bird flight under smooth and turbulent conditions. The relatively long test section gave sufficient distance for the generation of well mixed isotropic turbulence to be generated using planar grids.

A simplified illustration of the wind tunnel is provided in Fig. 2a. The tunnel has a closed-circuit configuration powered by a 225KW thyristor-controlled DC motor driving a six-blade single-stage axial fan. The test section speed can be infinitely varied from 0 to ~ 50 m/s and is measured using a Pitot-static tube connected to an MKS differential pressure measuring system. The tunnel has a contraction ratio of 2:1, and very low acoustic noise is present in the test section due to anechoic turning vanes. The wind tunnel has three flow-smoothing screens at the locations indicated in Fig. 2a. In this “baseline” configuration it has nominally smooth flow in the test section (turbulence intensity of 0.8%).

Modifications to the tunnel for this study included the ability to increase the turbulence levels to those found outdoors, the generation of a suitable updraft, and the introduction of features necessary to provide a safe flight environment for live birds and methods for changing the turbulence level. See Fig. 2b for a diagram showing the tunnel test section configured with these changes.

2.2 Flow Mapping

A target flight volume was defined, providing a region for flow mapping efforts, as well as a region on which to focus cameras for data acquisition (as shown in Fig. 2b). The flight volume was 1.35 m long, 1.5 m wide and 0.75 m high, and had a centroid located 1.325 m above the tunnel floor and 7.125 m downstream from the inlet.

Mapping of the flight volume was conducted by using arrays of point measurements from a TFI Cobra Probe mounted on a system of sliding rails. Cobra probes are commercially available pressure-based velocity measuring instruments that measure u , v and w components of fluctuating airflow velocity. The probes are relatively robust yet still have a flat frequency response to 2 kHz. Details can be found in [30]. Mean flow angle, velocity and the turbulence intensity were calculated at each location from one-minute samples. The xz plane located at the centre of the test section was mapped using a square grid with 0.15 m spacing. Mapping was conducted with and without turbulence grids and at tunnel speeds of 5, 6 and 7 m/s.

2.3 Updraft Generation

An updraft was created by placing an obstacle to the flow on the floor of the wind tunnel test section. Several obstacle geometries were trialled; however, a ramp was found to produce the most desirable updraft characteristics. The ramp used had a surface length of 1.215 m and was inclined at an angle of 52 degrees. The leading edge of the ramp was positioned 7.14 m downstream from the test section inlet and raised 0.145 m above the tunnel floor allowing the test section's boundary layer to pass underneath maintaining smooth flow over the ramp.

2.4 Turbulence Generation

Turbulence was generated using grids following the prior studies relevant for road vehicles and UAVs [31–33]. The grids consist of flat panels of different widths and spacings and by varying the size and spacing of the grid, the turbulent properties (length scale and intensity) can be controlled. The wake immediately downstream of the grids is dominated by vortices shed from the grids, however these decay into homogeneous isotropic turbulence as the flow travels downstream. Therefore a long test section is required to achieve well-mixed turbulence. The turbulence length scale and intensity likewise decay as downstream distance from the grids increases.

Two grid configurations studied by Ravi [33] were used in this study. Both grids are comprised of 0.275 m wide flat panels arranged in a 1 m square spacing with openness ratio of 0.49. The grids have been labeled A and B based on the locations indicated in Fig. 2a. Grid A is located at the entrance of the contraction chamber and produced turbulence with a longitudinal turbulence intensity of 7.3% and longitudinal length scale of 0.22 m at a point 7.75 m downstream from the test section inlet and 1.3 m above the tunnel floor. Grid B was located at the test section inlet and produced a turbulence intensity of 12.6% and a longitudinal length scale of 0.31 m at the same location. These turbulence intensities are in the range of those measured in outdoor environments at windhovering locations. The length scales are small relative to those of the atmospheric boundary layer, however, they will nevertheless provide significant perturbations to birds or aircraft of a similar scale [34].

2.5 Flight Trials With Live Kestrels

Ethics approvals for flight testing with live birds were obtained from the RMIT Animal Ethics Committee (approval number 1804) and the Victorian State Government Department of Environment, Land, Water & Planning (approval number 10008735). Flight testing was conducted accordance with relevant guidelines and regulations. Testing was conducted in accordance with applicable ARRIVE guidelines.

2.5.1 Kestrels

Two nankeen kestrels (*Falco cenchroides*) were selected for flight trials. Both birds are females, were raised in captivity, and were already trained to fly indoors. Modifications were made to the test section to ensure the kestrels' safety including installing fine mesh netting upstream and downstream of the test section to ensure it was inaccessible to the birds. The birds were food motivated, and the granting or withholding of rewards was used to train them to fly in the manner and location desired. Rewards were

attached to falconry lures that were concealed beneath a cover on the test section floor. After successful windhovers the baited lures were pulled into the open, allowing the birds to access their rewards.

2.5.2 Motion Capture

An array of 13 Qualisys Oqus 7 + infrared motion-capture cameras and three Miquis M5 optical cameras can be mounted along the walls of the test section to capture the position of hemispherical reflective markers (with a diameter of 1.5 mm and 3 mm) placed on the bird's feathers using double-sided adhesive tape. The distribution of the markers can be varied, however, for this study markers were placed on the centre of the kestrel's mantle and used to record the location of hovers during flight trials. The motion capture system was calibrated before each flight run and the measurement noise was < 0.4 mm.

3 Results And Discussion

Characteristics of the updraft measured at the central plane ($y = 0$) are presented in Fig. 3. Figure 3a is a scale diagram depicting the relative positioning of the flight volume and ramp within the test section, the updraft streamlines in the mapped volume, and a silhouette indicating the relative size of a kestrel. Figures 3b and c contain contour plots displaying the flow velocity and angle of the updraft in the centre of the test section at a tunnel speed of 6 m/s. The circular blue markers indicate locations of flapless windhovers found during tests with kestrels.

Comparisons between mapping conducted at tunnel speeds of 5, 6, and 7 m/s found little variation in updraft characteristics. When normalised by tunnel velocity, updraft velocities differed by less than 2%. Updraft angles differed by less than 0.5 degrees.

In the baseline configuration (no grids) the tunnel flow was nominally smooth (turbulence intensity of typically $\sim 0.8\%$). With grid A installed, the turbulence intensity ranged from 5 to 7.5% in the flight volume. Grid B produced a turbulence intensity between 8 and 13%. In both cases, the highest turbulence intensities were measured closest to the surface of the ramp due to the presence of a developing boundary layer.

3.1 Updraft Characteristics

The updraft velocity and angles produced in the wind tunnel are representative of those reported in the literature. Updraft angles between 1 and 42 degrees were measured, with the target angles of 5 to 8 degrees running through the centre of the mapped volume. The tunnel was set to 6 m/s for the flight tests, which produced updraft velocities similar to those recorded in the literature. Both the updraft angle and normalised velocity are stable at different tunnel speeds, however, they can be tuned by adjusting the overall tunnel speed and ramp angle.

3.2 Flight Results

For the purposes of this paper, flight testing was conducted without turbulence grids installed, thus the airflow was smooth. The results confirmed that the tunnel configuration does indeed provide conditions suitable for windhovering and soaring flight within the target volume. The kestrels successfully exhibited hanging flight across a range of local speeds and updraft angles, however hovering locations are clustered around an updraft angle of 10 degrees. The distribution of hover locations is qualitatively similar to the distribution of gulls flying in updrafts created by buildings [35].

Local updraft angles for each hover location were interpolated from the mapped contours. The mean updraft angle at hover locations was 10.3 ± 2.0 deg s.d., $n = 63$. Most flights occurred at updraft angles greater than those reported by Videler (5–8 degrees) [1]. The wind speeds at hover locations during our testing were relatively low (6.9 ± 0.6 m/s s.d., $n = 63$) compared to those *estimated* by Videler (7–12 m/s). Turbulence characteristics cannot be compared as Videler did not record them. It is important to note that Videler's study estimated wind conditions at kestrel's windhovering locations based on mean wind profiles calculated from prior measurements. This provides a rough estimate of the wind at hover locations, but cannot be relied upon to provide accurate values. The controlled flow of the wind tunnel in this study provides far greater confidence of wind conditions at hover locations.

4 Concluding Remarks

The airflow conditions required for soaring and windhovering flight in nature were reviewed and reproduced via modifications to the RMIT Industrial Wind Tunnel. Flight trials with nankeen kestrels confirm that this facility is suitable for the study of soaring and windhovering bird flight.

Using this method existing wind tunnels may be easily configured for the study of continuous gliding bird flight, eliminating the need to construct dedicated wind tunnels with tilting test sections. Tunnels equipped in this manner may be used to study gliding birds in smooth flow, mixed turbulence, or discrete gusts. Such studies could focus on the aerodynamic performance of gliding flight, or the control responses used by birds to mitigate gusts or turbulence. The facility could also be used to test the flight performance of UAVs in simulated atmospheric turbulence.

Declarations

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Author Contributions

Methodology: A.M., G.Y., M.P. & S.W.; Data collection: G.Y., A.M., & S.W.; Data analysis: G.Y. & M.P.; Writing: M.P., G.Y., S.W., A.M. & S.P.W.; Supervision: A.M., S.W. & S.P.W.; Funding Acquisition: A.M., S.W. & S.P.W.

Competing Interests

The authors declare no competing interests

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1

Temporal and spectral characteristics of wind measured at a location on the Gower peninsula in the UK where birds have been observed to windhover. a) shows a 10 minute sample of the fluctuating wind velocity measured by four TFI Cobra Probes. The velocity from each of the four probes is shown in a different colour. b) shows the power spectral density of the flow follows the -5/3 Kolmogorov spectral decay depicted by the blue line.

Figure 2

The RMIT Industrial Wind Tunnel used to facilitate soaring and windhovering flight. a) A schematic of the RMIT Industrial Wind Tunnel, adapted from Ravi [19]. b) The test section configured to facilitate soaring and windhovering birds.

Figure 3

Results of flow mapping and flight testing conducted at a tunnel speed of 6 m/s. a) The relative positioning of the flight volume and ramp within the wind tunnel. The streamlines in the flight region are depicted, as well as a silhouette indicating the size of a kestrel. b) Contours of the velocity and c) updraft angle within the flight volume. Blue markers indicate the locations of hanging flight observed in flight trials with kestrels.