The Physics of Bird Flight: An Experiment

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This article describes an experiment that measures the forces acting on a flying bird during takeoff. The experiment uses a minimum of equipment and only an elementary knowledge of kinematics and Newton's second law. The experiment involves first digitally videotaping a bird during takeoff, analyzing the video to determine the bird's position as a function of time and its flapping rate, calculating the velocity of the bird's wings, and finally, inserting those results into Newton's second law of physics. The experiment has been designed for a high school physics class. This article is a follow-up on our recently published theoretical article on the origin of bird flight.[1]

The theory behind this experiment is as follows: for a bird traveling in the horizontal direction, there are two forces acting in the vertical direction—the vertical component of the aerodynamic force upward and gravity Mg downward, such that

$$R \cos \theta - Mg = Ma_y = 0, \tag{1}$$

where θ is the angle between the aerodynamic force and the vertical axis, M is the mass of the bird, g is the acceleration due to gravity, and a_y is the vertical acceleration, which is zero for horizontal flight.[1] The application of Bernoulli's equation to the flow of air moving faster over the bird's wing than under the bird's wing gives rise to the classically simple, steady flow aerodynamic force

$$R_c = \frac{1}{2}\rho S {V_{\text{rel}}}^2 C_L, \tag{2}$$

where ρ is the density of air, 1.225 kg/m^3, S is the area of the bird's two wings, V_{rel} the velocity of the bird's wings with respect to the air (which is assumed to be at rest with respect to the Earth), and C_L the coefficient of lift, usually having a value around 1.[2] $\mathbf{V}_{\text{rel}}$ is the vector sum of $\mathbf{V}$, the velocity of the bird with respect to the Earth, and $\mathbf{V}_w$ the velocity of the downward moving wing with respect to the bird's body. The force $\mathbf{R}_c$ is perpendicular to $\mathbf{V}_{\text{rel}}$. The goal of the experiment is to measure $R_c \cos \theta$, insert it into Eq. (1), and see if the equation is satisfied. If it is not satisfied, then we have to look for other contributions to the aerodynamic force.

The experimental procedure consists of one student chasing a bird and another stationary student digitally videotaping the bird running and then taking off into flight. In our case, we chose the Canadian goose as our subject because (1) they are common on our campus, (2) they usually take a running start before taking off, and (3) after takeoff they fly in a horizontal direction before soaring upward. (2) and (3) are indications that R_c plays a major role during takeoff.[1] Because the Canadian goose is a protected species, permission from the campus Institutional Animal Care and Use Committee was received before the experiment was attempted. A Sony Model DCR-DVD-105 digital video camera was used to photograph the bird, Handbrake software was used to rip the video file into mpeg format, and iMovie software displayed individual frames. Individual frames every 0.12 seconds were printed; a sample frame is shown in Fig. 1. Using the printed sheets, the location of

DOI: 10.1119/1.2840979

Fig. 1. Frame 9 from the digital video.

the goose in each frame was determined by returning to the site of the videotaping. The distance the goose traveled between frames was then measured. A list of the positions at each frame and the calculated average velocities between the frames are found in Table I.

Inspecting the individual frames and the table, the goose leaves the ground in frame 6, so **V**, the velocity of the goose at takeoff, is about 2.7 m/s in the horizontal direction. At the time of takeoff, the flapping rate is observed to be 4 Hz, and the wings sweep out about $\pi/2$ rad during each downstroke. Following the approach of Burgers and Chiappe,[3] we can roughly estimate $\mathbf{V}_\mathrm{w}$ as follows: First, assume that $\mathbf{V}_\mathrm{w}$ is only in the vertical direction. Second, take the wing's angular velocity as $\pi/2$ rad divided by half a period, 0.125 s. Third, take $\mathbf{V}_\mathrm{w}$ to be 0.375 of the bird's wing span multiplied by the angular velocity during the downstroke. The mass, wingspan, and area of both wings of an adult Canadian goose have been measured as 4.7 kg, 1.5 m, and 0.33 m^2, respectively.[4] Then, $V_\mathrm{w} = 7.1$ m/s; $V_\mathrm{rel}{}^2 = V_\mathrm{w}{}^2 + V^2 = 57$ m^2/s^2; and $\cos\theta = V/V_\mathrm{rel} = 0.36$. Taking C_L as 1 gives an $R_\mathrm{c}\cos\theta$ from Eq. (2) of 4 N (this is probably an over estimate, since the much smaller $R_\mathrm{c}\cos\theta$ during upstrokes has not been included). The force of gravity is 46 N. Clearly Eq. (1) is not satisfied by setting $R\cos\theta$ equal to $R_\mathrm{c}\cos\theta$.

What is missing in this analysis is the creation and shedding of vortices by the bird's wings. In simple terms, during downstrokes vortices are created primarily above the wings, generating high circular speeds in the air and thus, by Bernoulli's equation, lower pressures.[2-5] In the case of the Canadian goose during takeoff, it is this vortex creation that is the primary contributor to the aerodynamic force acting on the bird. It is important to mention that this vortex creation and shedding contribution to R during down-strokes only make sense if there is no equal and opposite vortex creation and shedding contribution to R during upstrokes. In the case of modern birds, during upstrokes they both spread their feathers apart so that air flows through them, thereby equalizing the pressure above and below the wings, and they bend their wings so the cross-sectional surface area is reduced.[2,4] Finally, as the bird picks up speed after takeoff, the contribution of $R_\mathrm{c}\cos\theta$ to the aerodynamic force becomes more important. In frame 18 when the goose is traveling at 8.3 m/s, $R_\mathrm{c}\cos\theta$ is comparable to the vortex creation and shedding contribution.

Table I. The positions of the goose in each frame of the video and the average velocities of the goose between frames of the video.

Frame	Time (s)	Position (m)	Average Velocity
1	0	0	0.8
2	0.12	0.09	1.75
3	0.24	0.30	1.33
4	0.36	0.46	2.5
5	0.48	0.76	2.8
6	0.60	1.1	2.5
7	0.72	1.4	2.1
8	0.84	1.65	5.1
9	0.96	2.26	4.0
10	1.08	2.74	5.3
11	1.20	3.38	4.8
12	1.32	3.96	6.1
13	1.44	4.69	5.1
14	1.56	5.3	5.1
15	1.68	5.91	6.1
16	1.80	6.64	6.7
17	1.92	7.44	8.3
18	2.04	8.44	

It is of biological interest to speculate about how *Archaeopteryx*, the earliest known bird, learned how to fly. This is a part of a 100-year-old debate about the origin of bird flight, namely whether it was ground-up or tree-down.[1] The same force analysis that we applied to the Canadian goose can be applied to *Archaeopteryx*. From the fossil record, it has been estimated that the mass of *Archaeopteryx* was about 0.2 kg, the area of both wings was 0.05 m^2, and the maximum running speed was 2 m/s.[3] With these values, $R_\mathrm{c}\cos\theta$ is roughly a factor of 10 less than the force of gravity. For the ground-up approach to work, Burgers and Chiappe have suggested that *Archaeopteryx* must have developed muscle-powered flight while running on the ground in order to generate the needed aerodynamic force to both run faster and to take off.[3] In contrast, in the tree-down gliding or flutter-gliding approaches, gliding or fluttering could have slowly evolved into muscle-powered flight over millions of years.[2,6] This raises another very interesting historical question: When did birds develop muscle-powered flight—namely, the coordinated motion of the wings to generate vortices primarily during downstrokes? Before flying or millions of years after gliding and fluttering?

Acknowledgments

We want to thank Wayne Garver, Fred Willman, and Marcel Bechtoldt for their invaluable technical assistance. Support by the Pfizer/Solutia Students and Teachers As Research Scientists (STARS) program at the University of Missouri-St. Louis and by Nicholas Karakas and the Hellenic Spirit Foundation is gratefully acknowledged.

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PACS codes: 01.55.+b, 45.00.00

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