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LEONARDO DA VINCI'S DISCOVERY OF THE DYNAMIC SOARING BY BIRDS IN WIND SHEAR

by

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Although Leonardo da Vinci (1452–1519) is well known to have studied bird flight, few people realize that he was the first to document flight manoeuvres now called dynamic soaring. Birds use these manoeuvres to extract energy from the gradient of wind velocity (wind shear) for sustained flight. In his Manuscript E (*ca* 1513–1515) Leonardo described land birds performing flight manoeuvres that match those of albatrosses and other seabirds when they are engaged in dynamic soaring over the ocean. His description pre-dates by almost 400 years the first generally accepted explanation of the physics of this soaring technique by Lord Rayleigh in 1883. Leonardo's early description of dynamic soaring is one of his major aerodynamic discoveries.

Keywords: Leonardo da Vinci; bird flight; soaring; dynamic soaring; wind shear

Introduction

Most medium and large albatrosses exploit the increase of wind speed with height above the ocean surface for very long flight; wandering albatrosses even fly around the world in the Southern Ocean with minimal flapping of their wings. The exploitation of the gradient of wind velocity (wind shear) to extract energy for sustained soaring is the definition of dynamic soaring. Wind shear is the key to dynamic soaring of albatrosses, radio-controlled gliders and unmanned aerial vehicles (UAVs). Recently I discovered that over 500 years ago Leonardo da Vinci described the dynamic soaring manoeuvre in his sketches and notes.[1] Because of their importance to the history of aerodynamics I would like to describe Leonardo's findings below.

Dynamic soaring birds fly in a distinctive flight manoeuvre that is easy to recognize for those familiar with the flight of wandering albatrosses. The manoeuvre typically has four phases: starting with flight near the ocean surface, a bird (1) turns into the wind, (2) climbs upwind across the wind-shear layer, (3) turns downwind, and (4) descends downwind across the wind-shear layer, ending near the surface and headed in the original

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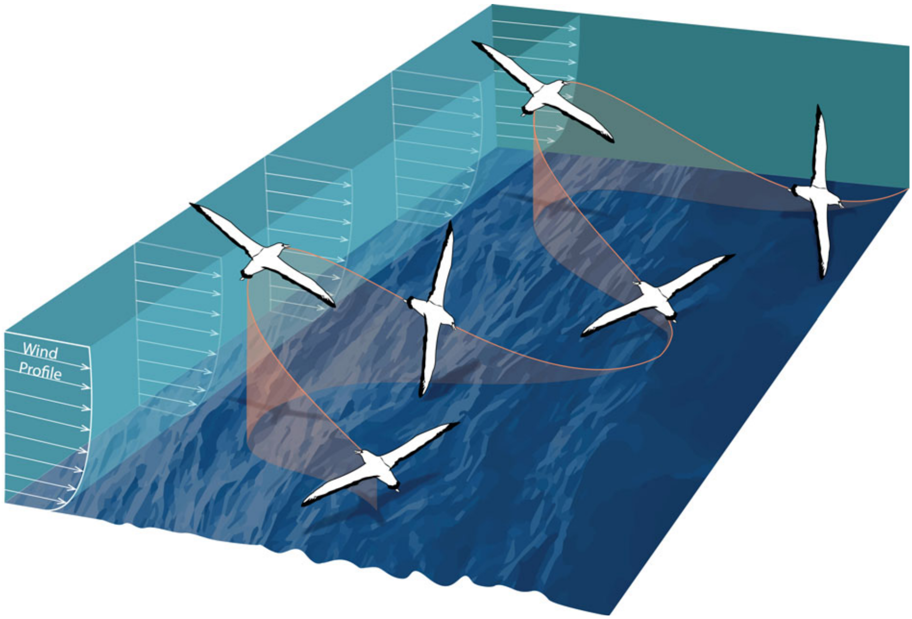

Figure 1. Schematic diagram showing an albatross flying in an across-wind direction using an S-shaped dynamic soaring manoeuvre. The albatross is soaring through a vertical profile of mean wind velocity. The bird extracts energy from the wind by climbing headed upwind, turning downwind and descending headed downwind. Significant waves are typically observed in the Southern Ocean. Wind–wave interactions cause a more complicated instantaneous wind field than that plotted here. Albatrosses appear to efficiently exploit instantaneous *in situ* winds and waves in dynamic soaring. (Online version in colour.)

direction (figure 1).[2] Across-wind flight typically consists of a series of approximately 90° turns and 45° diagonal climbs and descents relative to the across-wind direction.[3] Upwind and downwind flight can be achieved by adjusting the directions of the phases like a tacking sailboat.

Mechanical energy, defined to be the sum of kinetic energy relative to the air and potential energy relative to the earth, is gained during a bird's climb and descent across the wind-shear layer.[4] Since the beginning and ending airspeed and altitude of a dynamic soaring manoeuvre are unchanged, there is no net gain in mechanical energy. Drag reduces the energy gained in crossing the shear layer, resulting in energy-neutral flight.

Leonardo began to study bird flight when he was trying to develop human-powered flying machines. He paid particular attention to soaring birds in order to learn how they fly without flapping their wings. His manuscripts contain over 500 sketches of birds, bird flight and devices for human flight. In order to interpret his observations of soaring birds, he studied the movement of air and water and wrote:

> In order to give the true science of the motion of birds within the air, it is necessary first to give the science of the winds, which we shall prove by means of the motions of water within itself. And this perceptible science will become a model for arriving at the knowledge of flying creatures within the air and the wind.[5]

Although Leonardo is recognized for his remarkable studies of aerodynamics, few people realize that he was the first person to document dynamic soaring. The two most detailed sketches of dynamic soaring flight in his Manuscript E look like familiar dynamic soaring manoeuvres of albatrosses, and notes add confirming details. These sketches and notes appear to be the first ones in existence concerning dynamic soaring manoeuvres. Additional sketches show birds climbing vertically using both updrafts and dynamic soaring. A few examples are included here to show differences between these trajectories.

Methods

I became interested in Leonardo's description of soaring birds when I read a paper by P. Lissaman,[6] who mentioned that Leonardo had marvelled at the birds' ingenuity in using air movements to assist their flight, as described by D. Laurenza.[7] I was curious to find out if Leonardo had explained that birds could soar using energy gained from wind shear. If so, it would have been a major aerodynamic discovery and would push back the known date of the discovery by hundreds of years.

I started by reading Leonardo's well-known Codex on the Flight of Birds (CFB) (*ca* 1505), which had been on exhibit at the Smithsonian Air and Space Museum in 2013 with a translation and sketches available online.[8] The Codex was not very informative about birds using wind shear for soaring. I then read Laurenza's book and found it to be a good introduction to Leonardo's work on bird flight, with many illustrations about soaring from various manuscripts. Most importantly, it included two key sketches from Leonardo's Manuscript E (*ca* 1513–1515), which closely resembled dynamic soaring trajectories. However, Laurenza did not mention Leonardo's notes accompanying the two sketches and did not interpret them as dynamic soaring.

In order to investigate the possible dynamic soaring sketches in Manuscript E, I studied two English translations of Leonardo's manuscripts: one by J. Venerella,[9] and the other by E. MacCurdy.[10] MacCurdy helpfully collected all the sections on bird flight and placed them together in a chapter entitled 'Flight', which includes translations of 158 pages of 13 different manuscripts, including Manuscript E. Venerella recently translated Manuscripts A–M, which are located in the Bibliothèque of the Institut de France in Paris. Mainly, I have used his translation of Manuscript E here. The translations did not include images of Leonardo's sketches, which made them difficult to investigate, but John Venerella kindly provided a link to a website[11] that posted facsimiles of the manuscripts along with Leonardo's hand-written notes transcribed into printed Italian. This made it fairly easy to compare English translations of Leonardo's notes while viewing images of the associated sketches. Most of Leonardo's original recorded observations of bird flight appear to have been made near Florence around 1500–1506; Manuscript E, which is dedicated to bird flight and the science of winds, was compiled later (*ca* 1513–1515) when Leonardo was living in Rome. Manuscript E provides the most convincing evidence of dynamic soaring. The Codex Atlanticus, which contains folios from different periods (including *ca* 1503–1506), contains some very similar notes about bird flight as those given in Manuscript E and the CFB. I examined Manuscript E at the Institut de France and was struck by both the small size of this pocket notebook (roughly 4 inches by 6 inches), perhaps useful for field studies, and Leonardo's small, carefully drawn detailed sketches.

Over the years I spent many hours observing albatrosses engaged in dynamic soaring over the ocean, including wandering, black-browed, grey-headed, sooty, and light-mantled sooty albatrosses. I compared my observed manoeuvres of albatrosses to Leonardo's sketches and notes. It became clearly apparent that Leonardo had accurately sketched and described dynamic soaring manoeuvres of birds. Recent high-resolution trajectories of albatrosses measured by GPS also tend to confirm Leonardo's descriptions. I investigated early explanations of dynamic soaring in order to place Leonardo's knowledge of the physics of this type of flight in a historical context. I also read several papers and books that describe Leonardo's studies of aerodynamics and bird flight, but none mentioned dynamic soaring or identified his sketches and descriptions as illustrating dynamic soaring manoeuvres.

Brief history of dynamic soaring

To the best of my knowledge, before Leonardo's work, no aerodynamic analysis of bird flight existed. For example, R. Giacomelli says that, according to the science of Aristotle's time, birds flew because they had the property of flight.[12] Aristotle wrote that birds had their support on air as ships have theirs on water.

Leonardo's observations, sketches and descriptions of bird flight were a major step forward in the study of aerodynamics. His aerodynamic concepts were amazingly advanced for the time; he has become recognized as a genius for his art and his notebooks about science and engineering. Some major contributions are the law of continuity, his observations and sketches of fluid flow patterns, the statement that air resistance is directly proportional to the area of the body, the concept of streamlining a body to reduce drag, and the statement of the 'wind tunnel principle' that aerodynamic results are the same whether a body moves through stationary air or the air flows past a stationary body.[13] Curiously, historians of aerodynamics[14] seem to be unaware of Leonardo's discovery of the aerodynamic flight manoeuvre that birds use for dynamic soaring. I have not found any detailed studies of Leonardo's description of dynamic soaring.

Lord Rayleigh is generally accepted as being the first person to realistically explain how a bird could gain energy from wind shear for sustained soaring.[15] In his 1883 paper he assumed a two-layer wind step model in which the wind speed increased by ΔW vertically across the step. A dragless bird crossing the step headed upwind at a shallow angle with the horizon would gain airspeed of ΔW and descending across the step headed downwind would gain another ΔW, resulting in a net gain of $2\Delta W$ in a circle. If the wind speed increased by 5 m/s across the step, a bird could increase its airspeed in a circle by 10 m/s. When this increase of airspeed equals the loss of airspeed due to drag, then a bird can soar for long times and distances. Rayleigh noted that this would also be true for a continuous increase of wind speed with height; if wind shear were sufficiently large, a bird could use the excess airspeed gained to increase altitude.[16] Rayleigh did not call the manoeuvre dynamic soaring, but Manchester did later,[17] and the term has since become common usage. 'Dynamic soaring' will be used here to mean soaring by extracting energy from wind shear, noting that neither Leonardo, Rayleigh nor some others used this term.

Rayleigh's conceptual model of dynamic soaring was stimulated by observations of several kinds of birds (e.g. vultures, pelicans and adjutants) that spiralled upward in trajectories tilted downwind by wind as described by S. E. Peal.[18] Rayleigh investigated wind shear as a source of energy for this type of soaring. Most observers of upward spiralling flight conclude that it exploits ascending thermals, which raises the issue about how relevant dynamic soaring is to this type of flight at heights where wind shear is often not large. In 1883 Rayleigh did not know how large wind shear needed to be to support bird soaring. Subsequent observations would indicate that most dynamic soaring of birds is located in strong shear layers near ocean and land surfaces, not at great altitudes.

In 1889 A. C. Baines described the typical flight manoeuvre of albatrosses and concluded that they gained energy for soaring from the strong wind shear located near the ocean surface,[19] much as described by Rayleigh for birds at higher altitudes. Baines found that an albatross could gain airspeed in the manoeuvre amounting to approximately two times the difference of wind speed between the ocean surface and the height of the bird's upper turn. He described the upwind climb as follows:

> A bird's ascent against the wind may be compared with the ascent of a particle up an incline, while the incline itself is accelerated in a horizontal direction opposite to that of the particle's motion, thereby enabling it to reach a height greater than that due to the initial velocity.

The incline analogy is mentioned because Leonardo used a similar wedge analogy, but not an 'accelerated' wedge, which would be appropriate in wind shear. Shortly after reading Baines's paper, Rayleigh published a note acknowledging Baines's observations,[20] and said,

> there seems little reason to doubt that the true explanation of the flight of the albatross has been arrived at. In the case of the pelican soaring to a great elevation, it is less easy to understand how the difference in horizontal velocity can be sufficient.

In 1900 Rayleigh summarized bird soaring as part of a review of the mechanical principles of flight.[21] This was an important step because he was one of the few respected scientists promoting human flight in those days. Rayleigh included a discussion of: (1) dynamic soaring and said that it probably explained much of the sailing flight of albatrosses and seabirds, but that it was doubtful whether wind shear at considerable elevation in the atmosphere was sufficient to allow a bird to maintain his position without flapping his wings; (2) upward soaring in ascending air, both in updrafts caused by thermals and wind striking sloping land and being deflected upwards; and (3) soaring in wind gusts, concluding that it is quite possible for a bird moving in a very natural manner against a strong and variable wind to maintain itself over the ground without working its wings. He referred to the observations of E. C. Huffaker,[22] who had recorded many examples of vultures soaring in thermals rising from the ground when it was strongly heated by the sun. Rayleigh also mentioned Huffaker's observations of birds soaring against a strong and variable wind and S. P. Langley's measurements of the gustiness of the wind,[23] which a bird could exploit to gain energy for soaring.

Over the years there has been a debate about whether the main source of energy for albatross soaring is updrafts over waves or wind shear near the sea surface. Some scientists originally favouring updrafts changed sides in the argument to favour wind shear.[24] Dynamic soaring has now been accurately modelled,[25] and there appears to be a consensus that it explains most albatross soaring, at least in the windy Southern Ocean.[26] An exception to this is in low winds and large waves, when wave-forced updrafts can provide sufficient energy for sustained soaring, as mentioned by W. Froude.[27] Albatrosses probably also extract energy from wind gusts using dynamic soaring manoeuvres because wind gusts at low altitudes include increased wind shear. Some medium-sized and smaller albatrosses and other seabirds appear to use alternating periods of flapping and gliding (flap-gliding) to augment the energy obtained from wind shear and updrafts over waves, especially in low winds.[28]

The flight of wandering albatrosses measured by GPS has been analysed relative to the speed and direction of the wind and plotted in the form of a flight polar diagram for different wind speeds.[29] Results look similar to flight polar diagrams generated with numerical models of dynamic soaring gliders.[30] These data and simulations tend to show increasing ground speeds with increasing winds speeds in all directions relative to the wind direction except directly upwind. A major difference is that in their preferred across-wind direction,[31] wandering albatrosses reach a maximum flight speed of around 20 m/s in wind speeds greater than around 10 m/s (referenced to a height of 5 m), whereas simulated across-wind flight speeds tend to continue to increase in increasing wind speed, depending on the specific model assumptions. Wandering albatrosses probably limit their maximum flight speed to around 20 m/s in order to keep the total acceleration and wing loading below the strength of their wings. Albatross-sized radio-controlled (RC) gliders have been observed to increase their dynamic soaring speeds to over 500 miles per hour (224 m/s) using wind-shear layers generated by fast wind blowing over mountain ridges. The accelerations of the gliders in fast dynamic soaring manoeuvres reach around 100 times gravity, much too great for birds. The period of the fast RC glider circular loops is around 2–3 seconds; the frequent crossings of strong separated shear layers account for the extremely fast flight speeds.

Leonardo's description of horizontal dynamic soaring flight

Leonardo sketched an across-wind dynamic soaring manoeuvre by a small flock of migrating birds,[32] as shown in figure 2. He mentioned thrushes and other similar birds that fly in droves using the undulating manoeuvre shown in the figure. Leonardo described the soaring flight manoeuvre as follows:

> When it happens that birds flying in flocks make long journeys, and the wind, by chance, strikes them on the side, these receive a great favor in their flying. And this is because the flying is done by bounds [undulations] and without the aid of the wings [no flapping] since their incident motion [descent] is made beneath the [course of the] wind, with their wings somewhat narrowed, and along the direction of the destined journey. But the reflected motion [climb] is made above the [course of the] wind, and with the wings opened, it rises upward, against the approach of the wind and so this wind penetrates beneath the bird, lifting it toward the sky, like a wedge that penetrates under a heavy object placed on top of it. For this reason, birds that have been raised to their proper height which is equal in the beginning to the incident motion [descent]—these turn with their front toward their original path, always recommencing toward the path of their incident motion [descent], and the reflected motions [climbs] are always made against the wind.[33]

I have tried to clarify some of Leonardo's terms using the added square brackets after comparing Leonardo's notes with the associated sketches. In addition to these notes are some others, which similarly describe birds using dynamic soaring manoeuvres.[34]

The sketch and notes reveal that Leonardo was describing a flight manoeuvre very similar to the documented dynamic soaring flight manoeuvre of albatrosses (see figure 1). Since

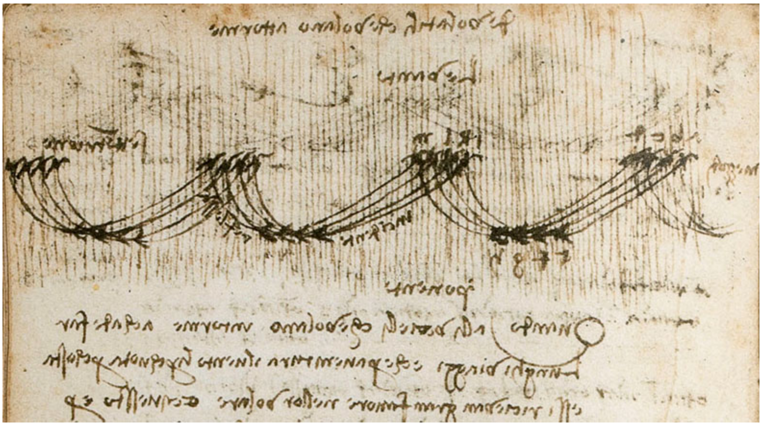

Figure 2. Leonardo's plan view sketch illustrating northward across-wind dynamic soaring (from right to left) of a flock of four birds along an undulating flight path. Straight lines indicate the direction of the horizontal wind, which is blowing westward from top to bottom of the page (from Leonardo's notes). The four phases of a typical dynamic soaring manoeuvre mentioned above can be identified starting from the right side with the birds climbing headed upwind and upward out of the page. The phases are described in slightly different terms in Leonardo's notes, which are written from right to left as can be seen using a mirror or a 'flip horizontal' computer command.

these birds tend to favour across-wind soaring, figure 2 is highly relevant. Leonardo appears to be the discoverer of the dynamic soaring manoeuvre. Although he did not mention wind speeds or the height of the birds above land, the implication is that there was sufficient wind since the birds' trajectories demand it.

Leonardo sketched downwind dynamic soaring,[35] as shown in figure 3. The fastest dynamic soaring ground speeds of wandering albatrosses tend to be located in the diagonal downwind direction. This is because the birds' fastest speed through the air is in the across-wind direction, and downwind leeway is combined with airspeed, which results in fast ground speeds. Therefore, Leonardo's sketches of across-wind and downwind soaring are typical examples of fast migrating flight. Both sketches show northward flight, which is consistent with migration in the Spring. He did not mention the species of the bird in figure 3, but he did mention various birds in his manuscripts, such as a cortone, crane, crow, eagle, fieldfare, kite, lark, pelican, sparrow, swallow and thrush. The only bird he mentions with a place and date is a cortone he saw on his way to Fiesole, near Florence, on 14 March 1505.[36]

Leonardo mentioned that deflected motion (climb) is always made against the wind, incident motion (descent) is made along the direction of the wind and the conjunction of the incident motion with the reflected motion is nearly always perpendicular.[37] This is interpreted to mean that the general direction of the descent is approximately perpendicular to the general direction of the climb. Leonardo's comment tends to agree with recent high-resolution trajectories of albatrosses soaring across-wind measured by GPS.

One noticeable difference between GPS trajectories of albatrosses and those of Leonardo's birds is that the upper turn is much sharper than the lower turn in both figures 2 and 3, which implies that the airspeed is significantly slower in the upper turn than the lower one. Albatross trajectories tend to look more symmetrical. This difference is probably due to the faster gliding cruise airspeed $\sim$16 m/s of the wandering albatross,

Figure 3. Leonardo's plan view sketch illustrating downwind dynamic soaring flight from right to left. The straight lines indicate the northward direction of the horizontal wind blowing from right to left. Starting on the right with a downwind descent the trajectory matches the four phases mentioned above and agrees with documented dynamic soaring manoeuvres but is slightly different from that in figure 2 for across-wind flight. Climbing is upward out of the page. Leonardo's notes were used to interpret the wind direction and soaring manoeuvre.

coinciding with a larger maximum glide ratio ~21.2 compared to the typical lower values of land birds. A bird with a large cruise speed and a large glide ratio has better aerodynamic performance and is able to glide faster and farther starting from the same altitude than a bird with smaller quantities. This is beneficial for dynamic soaring.

Leonardo offered the analogy of a moving wedge to explain how head wind lifts a climbing bird. If one assumes that a climbing bird encounters an increase of wind speed with altitude like the wind step Rayleigh described, then the wedge analogy would tend to agree with dynamic soaring. However, Leonardo did not mention an increase of wind speed with altitude in his notes about the dynamic soaring sketches, which implies that he might not have recognized it as being important to soaring. Leonardo might have intuitively recognized the importance of increasing wind speed with altitude but neglected to put it into words. Without wind shear (or wind gusts), the wedge analogy does not work dynamically because there would not be an energy source to counter drag and maintain a bird's altitude. In addition, the wedge analogy does not account for the second increase in airspeed mentioned by Rayleigh that is obtained in a downwind descent across the wind step. Leonardo did recognize that there was an increase of wind speed with altitude (wind shear): 'Birds always fly low when the course of the wind is contrary to their path and this teaches us how the wind is more powerful at a height than low down.'[38] Obviously the birds that actually used dynamic soaring for long-range flight perceived wind shear.

Leonardo described the dynamic soaring of land birds, not seabirds. In order to compare his descriptions with modern ones, I searched through the literature and asked various experts about bird flight for information. I found references to the dynamic soaring of swallows,[39] grey-faced buzzard eagles and Chinese sparrow hawks, among other (unnamed) species,[40] and of albatrosses[41] and gulls[42] dynamic soaring over flat land. I also asked two expert pilots of RC gliders, Chris Bosley and Spencer Lisenby, who frequently power their gliders with dynamic soaring using wind-shear layers formed near ridges and hills. Lisenby presently holds the unofficial RC glider speed record of 545 miles per hour (244 m/s) achieved by dynamic soaring an albatross-sized glider near Bird

Figure 4. Leonardo's sketch of winds encountering vertical cliffs and being deflected upward. Birds are supported by the ascending air.

Springs, California.[43] Bosley and Lisenby told me that they often see swifts dynamic soaring along the same ridges used by RC gliders, the swifts occasionally coming close enough to the glider pilots that they can clearly see them and hear the sound as the swifts pass through the wind-shear layer. They have also seen dynamic soaring crows, ravens, falcons and vultures. Vultures were observed to exploit updrafts on the windward side of ridges to use dynamic soaring over and downwind of the ridges and updrafts in thermals. The tendency is for birds to use dynamic soaring when wind is strong and thermal soaring when the wind is weak, especially during the day when the sun heats land and thermals are strong. It seems possible that Leonardo's sketches are of birds exploiting wind shear caused by interactions of wind and land features and the resulting detached shear layers similar to the birds observed by pilots of RC gliders.

Birds climbing in updrafts

Leonardo sketched and described two methods birds use to soar upward in ascending wind currents. The first occurs when wind strikes the steep sides of mountains or cliffs of the sea and is deflected upward,[44] causing ascending currents which can carry birds upward and with which they can maintain their altitude while they head into the wind (figure 4). The second method is when a bird spirals upward in a column of ascending air like a thermal,[45] although Leonardo did not mention warm air rising (figure 5). Today, this kind of soaring in an updraft is often referred to as static soaring. The trajectory in figure 5 is different from climbing trajectories in wind shear.

Leonardo's note accompanying his sketch in figure 5 is:

> When the bird rises in circles above the wind without beating its wings, using the ascending currents, it will be carried far from the area to which it wishes to return, even without beating its wings. Then it will turn its head in favor of wind, coming in with an inclination to the wind, losing lots of height, until it arrives above the place where it wants to return.[46]

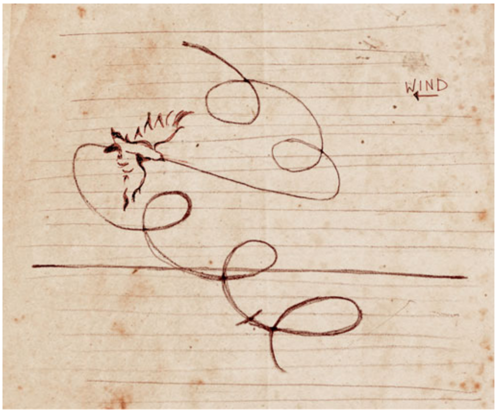

Figure 5. Leonardo's sketch of a bird ascending in what are interpreted to be two thermals. The bird circles upward as wind blows from right to left, tilting the upward trajectory in a downwind direction. After being displaced downwind, the bird descends heading into the wind toward its origin and starts climbing in a second upward trajectory. This sketch was redrawn from a lower resolution image. Wind direction is indicated by an added small arrow and label.

Birds climbing using vertical shear of horizontal wind

Leonardo sketched birds climbing using dynamic soaring (figures 6 and 7) and added descriptive notes. Both trajectories are interpreted to show flight in an average upward direction. Below the sketch[47] shown in figure 6 Leonardo wrote:

> When the bird, through the favor of the wind, rises without beating its wings and makes circular motion, and when he shows its tail to the origin of the wind, this is driven by two powers, of which the one is that of the wind, which strikes it in the concavity under its wings. The other is the heaviness of the bird, which descends in composite obliquity. And by this acquired velocity, it occurs that when it is turned with its breast against the coming of the wind, this wind goes beneath the bird like a wedge lifting a weight upward. And thus the bird makes its reflected motion [climb] considerably higher than the beginning of the incident motion [descent]. And this is the true reason that birds rise without beating their wings.[48]

Adjacent to the sketch[49] shown in figure 7 Leonardo wrote:

> This is the way in which the bird rises high, without the need to beat their wings and making circular trajectories. The remaining part of this circle is completed with the thrust of the wind, by upward movement, always with one of the wings lowered and one side of the tail lowered as well; and it then makes a reflex movement [climb] in the direction of the wind and in the end remains with its beak turned in the direction of the wind before incidental movement [descent] again takes over, then reflex [climb], always circling.[50]

The notes are somewhat confusing and do not explain the sketches very well. The trajectories can be interpreted to show usual dynamic soaring manoeuvres; the trajectory in figure 6 has longer upwind climbs and shorter downwind descents; the trajectory in figure 7 has a series

Figure 6. Flight trajectory interpreted to show upward dynamic soaring by alternating longer upwind climbs and shorter downwind descents, connected by turns to the right and left (upper sketch). The viewer of the upper sketch is interpreted to be facing into the wind. The lower sketch illustrates the 'breast against the coming of the wind' manoeuvre for wind blowing from right to left.

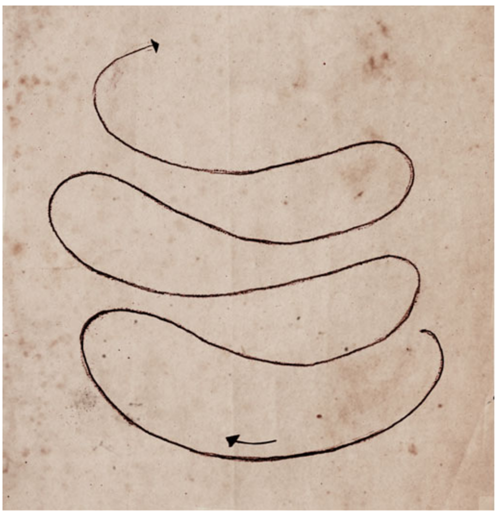

Figure 7. Flight trajectory interpreted to show upward dynamic soaring by alternating upwind climbs and downwind descents with alternating turns to the left and right. The viewer is interpreted to be facing into the wind. Leonardo's sketch was redrawn from a lower resolution image. Arrows were added to indicate the bird's flight direction.

of upwind climbs connected by mainly across-wind trajectories, which appear to have downwind components. The trajectories consist of a series of short tacks, like a sailboat tacking into the wind, as the birds gradually gain altitude. Tacking into the wind while climbing has the advantage of preventing a bird from being carried far downwind by leeway. The two trajectories are similar to some numerical simulations of upwind dynamic soaring trajectories,[51] with the exception of the small loops on the right and left sides of figure 6. Both of these trajectories are more complicated than the simple circling climb in a thermal (see figure 5), indicating that a thermal was not the source of energy for the upward motion.

A numerical simulation of wandering albatross soaring over the ocean found that dynamic soaring could be performed in wind shear consisting of a 3.8 m/s increase of wind speed over an 18.5 m increase in altitude in the flight manoeuvre.[52] This is equivalent to an average increase of wind speed of around 0.21 m/s per metre of altitude. The implication is that wind shears over 0.21 m/s per metre could support either faster flight or the vertical climbs that Leonardo sketched (assuming the wind shear extended as high as the altitudes of the sketched birds).

Leonardo states: ‘The kite and other birds do not flap their wings very much, but seek the current of the wind. When the wind is strong in the sky, then you always see them flying at great heights, but when the wind is light they are low.’[53] Flying in strong winds and strong implied wind shears at great height could be interpreted to be dynamic soaring, but it could also be a result of extracting energy from the turbulence or gustiness of strong wind, perhaps using dynamic soaring manoeuvres.

Leonardo used the same wedge analogy for vertical climbs as he did for across-wind and downwind dynamic soaring, saying that the bird heading upwind is lifted upward by a wedge of wind striking under the wings. He said that the main lifting occurs when the bird is turned with its ‘breast against the coming of the wind’, which is very similar to two recent descriptions of how energy is gained in dynamic soaring. Pennycuick mentions that the typical behaviour of albatrosses as they pull up out of a separation bubble is to ‘roll belly-to-wind’ to a very steep angle or bank when crossing a wave crest to windward.[54] Lissaman describes that a simple rule for gaining energy from wind shear is keeping the ‘belly to the breeze’ so that the lift vector is inclined in the direction the wind is blowing, which will enable the wind to do work on a bird.[55] Lissaman’s explanation is a good, concise summary of the physics of extracting energy from the wind in dynamic soaring. Leonardo’s description about a bird gaining altitude in the wind is similar to these. Leonardo did not mention the height of birds climbing in dynamic soaring, but, based on subsequent observations, wind shear is not often suitable at altitudes very far above land and ocean, except perhaps when detached boundary layers extend downwind of hills and ridges.

Birds climbing using horizontal shear of wind

A sketch of two birds climbing near a tower is shown in figure 8.[56] Some of Leonardo’s sketches in the Windsor Castle Royal Library collection illustrate water flowing swiftly around the sides of model towers and extending downstream, with much slower water located close to the downstream side of the towers. A strong velocity gradient can be seen to exist between the sluggish flow downstream of the towers and the swift flow extending past their sides. The implication is that Leonardo also knew about horizontal wind shear.

He appears to describe the circling flight shown in figure 8 as follows:

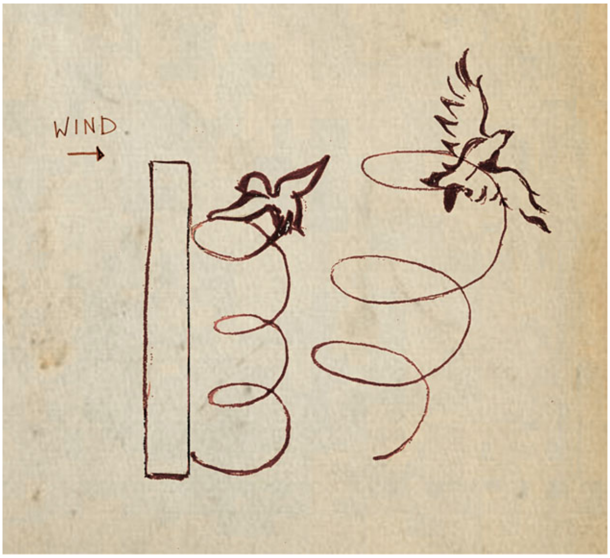

Figure 8. Two birds circling upward near a tower. The sketch is interpreted to illustrate dynamic soaring that extracts energy from horizontal gradients of wind interacting with a tower. Leonardo's sketch was redrawn from a lower resolution image. The interpreted wind direction is indicated by an added small arrow and label.

> When the bird wants, with its wings expanded, to make a circular motion that will lift it upward through the favor of the wind, then it lowers one of its wings and one of the horns of its tail toward the center of its circulation. And when the motion of the bird is circular, in order to lift itself upward without beating its wings, this receives the wind under one of the wings at one-quarter of its circulation, and thus the wind becomes a wedge for it and lifts it upward.[57]

Figure 8 and the above description indicate that a bird circling near the wind shadow of a tower periodically turns toward the swift wind flowing past the sides of the tower, resulting in an increase of airspeed that raises the bird like a wedge over a quarter of the circle. When the bird turns back downwind into the wind shadow and encounters another increase of airspeed, this manoeuvre could result in an upward spiralling trajectory without downwind descents as shown in figure 8. Lissaman once mentioned to me that Leonardo had described starlings 'riding the breeze' in and out of the wind shadows of the towers of Castello Guidi in Vinci in 1502.[58] I have, however, been unable to find the source of this information.

When I first saw the sketch shown in figure 8, I thought of a red-tailed hawk that I had watched climbing near the wind shadow of a tall building facing Central Park in New York City. I concluded that the hawk was using gradients of horizontal wind located between the wind shadow and the faster wind blowing around the sides of the building to extract energy and climb vertically using dynamic soaring as described above. I ruled out a thermal because the bird was soaring on the north side of the building, in the morning, in cold, windy winter weather, and after an overnight snowfall. I could easily have made a sketch of the flight manoeuvre like Leonardo's. My observation of the hawk formed the basis of my interpretation of figure 8.

Conclusions

Leonardo was motivated to discover how birds continuously soar in order to use this information for developing human flight. He made the first-known detailed descriptions of the dynamic soaring of birds. The soaring manoeuvres he identified are very similar to recent documented dynamic soaring manoeuvres of albatrosses extracting energy from the wind for sustained soaring. His detailed graphics of the dynamic soaring of land birds remain the best available today. Leonardo described both horizontal and upward dynamic soaring as well as upward soaring in updrafts. His sketches are excellent and his descriptions of the wedge analogy and 'belly to the breeze' manoeuvre are similar to some modern ones, although he never noted the importance of wind shear to dynamic soaring. Leonardo's observations pre-date by almost 400 years further advances in understanding dynamic soaring by Rayleigh, Baines and others.

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I have no competing interests.

Notes

1 P. L. Richardson, 'Da Vinci's observations of soaring birds', *Phys. Today* **70**, 78–79 (2017).

2 Figure 1 was redrawn from an illustration published by G. Sachs, 'Minimum shear wind strength required for dynamic soaring of albatrosses', *Ibis* **147**, 1–10 (2005).

3 G. Sachs, 'In-flight measurements of upwind dynamic soaring in albatrosses', *Prog. Oceanogr.* **142**, 47–57 (2016).

4 This is a description of the physical effects of gravity, wind shear and frictional drag on the climbing and descending flight of a soaring bird. The mechanical energy of a bird is defined to be the sum of the bird's potential energy relative to the earth (mgh) and its kinetic energy relative to the air ($0.5mV^2$). If drag is ignored, then the conservation of mechanical energy indicates that a bird starting with an initial airspeed V could gain altitude h proportional to V^2 as expressed by $h = V^2/2g$, where g is gravity. This indicates that it would be beneficial for a bird to start a climb with a large airspeed in order to not quickly run out of flyable airspeed. The decrease of airspeed with altitude is given by $\mathrm{d}V/\mathrm{d}h = -g/V$. Using the 16 m/s cruise airspeed of a wandering albatross, $\mathrm{d}V/\mathrm{d}h = -0.61$ m/s of airspeed per metre of altitude. In descending, a bird could equivalently gain airspeed as it loses altitude. If wind speed (W) increases vertically, a bird climbing headed upwind through the air at a relatively shallow angle α relative to the horizon could increase airspeed at around $\mathrm{d}V/\mathrm{d}t = (\mathrm{d}W/\mathrm{d}h)V\sin(\alpha)$. When this increase is balanced by the loss of airspeed due to gravity, $\mathrm{d}V/\mathrm{d}t = -g\sin(\alpha)$, then a dragless bird could climb steadily in wind shear equal to around $\mathrm{d}W/\mathrm{d}h = g/V$, which

equals an increase of wind speed of 0.61 m/s per metre of altitude at $V = 16$ m/s. The loss of airspeed due to drag can be expressed as $dV/dt = g/(L/D)$, where L/D is the lift-to-drag ratio of a bird. When this term is combined with those for gravity and wind shear in an analysis of the airspeed of a climbing wandering albatross, the minimum wind shear required for a steady climb at $V = 16$ m/s and $L/D = 21.2$ is around 0.74 m/s of wind speed per metre of altitude. (Wind shears of this magnitude are often found near ocean and land surfaces.) This minimum wind-shear value coincides with a climb angle through the air of around 20° relative to the horizon. If the bird turns and begins to descend headed downwind at 16 m/s and an angle of 20° below the horizon (for example), airspeed would accelerate at around 0.68 times gravity due to the sum of the positive effects of wind shear and gravity minus drag. It is thus apparent that, in sufficient wind shear, a bird could climb upwind without loss of airspeed, turn and descend downwind, and rapidly accelerate to a much faster airspeed. This clearly illustrates that mechanical energy is extracted from wind shear in both the climb and descent parts of a hypothetical dynamic soaring manoeuvre. Albatrosses can exploit significantly smaller wind shears than this for continuous dynamic soaring. For details of the calculation above, see S. L. Walkden, 'Experimental study of the 'soaring' of albatrosses', *Nature* **116** (2908), 132–134 (1925).

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31 In the typical across-wind flight mode consisting of approximately 90° (5 s) turns and 45° climbs and descents relative to the across-wind direction (see figure 1), the gain of airspeed ΔV in one crossing of a wind step ΔW is approximately equal to $\Delta W \sin(45°)$. The ΔW represents the increase in wind speed from near zero in a wave trough to a wind speed W blowing over the crest of a wave. In energy-neutral soaring, this airspeed gain ΔV is balanced by the loss of airspeed over 5 s as modelled by the quadratic drag law and the characteristics of a wandering albatross—a cruise airspeed $Vc = 16$ m/s coinciding with the maximum glide ratio = 21.2; see C. J. Pennycuick, *Modelling the flying bird* (Academic Press, New York, 2008). The minimum ΔW for dynamic soaring at Vc was found to be approximately 3.7 m/s. In principle, with a larger ΔW than this, an albatross could fly faster than Vc.

32 Manuscript E, folio 40v.

33 *Ibid.*

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44 Manuscript E, folio 42v.

45 CFB, folio 10r.

46 *Ibid*.

47 Manuscript E, folio 41v.

48 *Ibid*.

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50 *Ibid*.

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53 CFB, folio 5v.

54 Pennycuick, *op. cit*. (note 31).

55 Lissaman, *op. cit.* (note 25).

56 Manuscript E, folio 49v.

57 Manuscript E, folio 52v.

58 P. Lissaman, personal communication, 2010.