Aerodynamics of Birds' Flight

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Abstract

Avian flight has fascinated man from ancient times but is is only in recent years that the efforts of scientists from diverse fields have been able, to some extent, to understand and explain the dynamics of bird flight. Observations show an incredible diversity of flight techniques and manoeuvers. A general description of the main types of bird flight and some illustrations of wing shapes and the different motions of birds are given. A description of the structure and musculature of wings and feathers and elementary theories of flight and drag are also included. The article is nothing but a laborious collection of various information regarding the interesting topic of bird flight, which involve a deep knowledge of anatomy, biophysics, ornithology and aerodynamics. This complex subject is discussed here in a lucid manner so that even a reader unfamiliar with the subject can understand it easily.

1. Introduction

Ever since recorded time, man has watched birds fly through the sky and marveled at the ease with which they accomplish this flight. They take off, fly with twists and turns, soar and dive, and land again on a tiny branch, all with effortless precision. Fossil record shows birds have been flying for millions of years; although, it has only been within the last hundred years or so that man has truly begun to comprehend the complexities of flying. In 1901 Wilbur Wright remarked, "a bird's skill as a flier is not apparent. We only learn to appreciate it when we try to imitate it". No matter how hard he tried to fly, man had to unravel the mysteries of flight. He had to first understand the forces on earth that enable flight, and then to try and duplicate a bird's actions. It wasn't until technology enabled him to develop an internal combustion engine that he overcame the difficulty of minimum weight and maximum power, something nature conquered long ago. Also, the invention of the slow motion camera enabled man to capture the split second motion of a bird's wing in flight. He could now see what had been impossible to see before, and could master controlled flight. All of nature's secrets of flight, thus, has been conquered by man with his brain and technology.

Nature first conquered the skies with insects, about 400 million years ago. Their fast-flapping flight enabled them to successfully span the globe; however, because of their size, insect flight is haphazard and not generally considered a controlled flight. A bird, on the other hand, is a perfectly controlled, very sophisticated, natural flying machine. Propellers, wings, flaps, and stabilizers are all secrets birds alone have shared for a very long time. Everything about every bird is designed for flight no matter what combination of attributes they possess.

Although man has observed birds for thousands of years, the scientific study of birds, called ornithology, did not begin until sometime in the 1700s. By only direct observation, many physical characteristics of a bird become immediately apparent. This article examines some general features of the bird flight-the flight apparatus of the bird and the modalities of the flight. Man learnt to build aircraft, by studying birds. Pioneers like George Cayley (1773 - 1857) in England, E. J. Marey (1830 - 1904) in France and Otto Lilienthal (1849 - 1896) in Germany were among the earliest scientists who not only observed birds but also analyzed their flying. Marey was among the first to realize that birds in flight could be properly studied only through high-speed photography. More modern work by Brown , Pennycuik, and Tucker have helped clarify the essential aerodynamics. In

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India, Salim Ali (1896 - 1987), the great ornithologist, worked a lot in this field.

2. What It Takes to Fly

In order to understand the natural flight of birds, one must first examine the essential elements necessary for flight. These are :

- a lighweight high-strength structure;
- wings and feathers for generating lift and forward thrust;
- flight muscles to provide power;
- a fast response flight control and navigation system.

Each of these is briefly discussed here,

2.1 The structure adapted for flight

The skeletal structure of the birds has evolved into an efficient lighweight structure consisting of the body box-the rigid ribcage-with the many vertebraed neck and flexible tail. The skeleton is essentially a frame for attachment of the movable wings and the powerful flight muscle to the deeply keeled breast bone, and has evolved to suit the demands of walking and flying. Most of the larger bones are hollow (sacs filled with air) and criss-crossed with supporting struts inside (see figure 1).

Birds have fewer bones than most animals. The wing bones are long and thin but very strong. Some bones have diagonally placed struts in them for added strength. Bent or braced materials are often very strong for their weight. A bird's skull is paper-thin. Also beaks are very lightweight; even a Toucans' beak is made of extremely light and porous layers of bony material. The biggest bones in flying birds are the breast-bone and the shoulder bones. The muscles that move the wings are attached to these bones. The breast bone in birds has become enlarged, shaped like a keel, and is very strong to support these powerful flight muscles. Generally, the size of the keel is proportionate to the flying power of the bird. So the more the wing muscle, the larger is the keel.

Comparison of the weight of a bird's skeleton with the weight of the rest of its body is a good way to tell how well a particular bird flies. Generally, the best gliding and soaring birds have the lightest skeleton. Some have bones weighing less than their feathers. The powerful flying birds have medium weight skeletons. Non-flying birds have the heaviest skeleton.

2.2 Wings and feathers

The most noticeable features of the bird's flight structure are the feathers and wings. Figures (1) and (2) show the details. Feathers are light but very strong, and they are flexible but very tough. A bird's body appears to be covered with feathers, but actually it is not so. Feathers grow only in certain areas called feather tracks. The contour feathers overlap so they appear solid, but limiting the number of feathers helps to keep down the body weight. In between the feather tracks, the down feathers or the semi-plumes grow. Feathers are made of a tough but flexible material called 'keratin'. The spine down the middle, called the 'shift', is hollow. The 'vanes', which are two halves of the feather that spread out from the shaft, are made of thousands of branches called 'barbs'. These angle toward the tip of the feather. Each barb has tiny parallel branches called 'barbules', which interlock like a zipper. Because a feather has all these tiny parts with spaces in between, a feather has as much air as matter.

Birds have 1,000 to 25,000 feathers, depending upon the species. Feathers can be divided into six categories. The contour feathers are the most abundant and cover the outer surface of the bird, giving the smooth, sleek profile so important to flight. The other types include semi-plume, down feather, filo-plume, bristles and powder-down feather.

The feathers on the wing are the flight feathers or specialized contour feathers. They have an especially rigid shaft. The vanes provide a lightweight, broad surface that pushes on the air to make flight possible. There are three kinds of flight feathers on each wing. The primaries are attached to the outer part of the wing, to the hand and finger bones. There are between nine and twelve on each wing. The inner part of the wing has the secondary. Again the number varies by species; hummingbirds have 6 of 7 and large birds have as many as 32. The tertiary are attached to the upper wing (See figure 1).

A bird's wing is the basic structure for flight. It is covered with contour feathers that are specialized for flight. It is the shape of the wing that enables a bird to fly, and the shape is determined by the feathers. In the long evolution process, the forelimbs were transformed into wings. The bone structure of a bird wing (see figure 2) is analogous to the human arm, wrist the fingers with obvious differences. The upper arm, 'humerus', is proportionately shorter. The 'wrist' and 'palm' bones are fused together for greater strength in supporting the primary flight feathers. Of the three fingers, two support feathers. The third, 'alula' supports a small auxilary wing extendable at will. This controls the airflow over the wing during landing and take-off manoeuvers-somewhat akin to leading edge slot or flap on aircraft.

It is critical that air flows evenly around and over the wings during flight so that friction and drag are kept at a minimum. The surface of the wing is kept smooth by the overlapping placement of the flight feathers. Each feather is also shaped so that the side facing the wind is narrower and stiffer than the trailing edge, which makes it stronger. In addition, along the leading edge (front) of the wing, are smaller contour feathers, called 'coverts', which cover the base of the flight feathers. These feathers give the wing the airfoil shape that make flight possible (see figure 3).

Although the curved airfoil shape of the wing is necessary to lift the bird into the air, feathers contribute much more during flight. On the up stroke of the wing, the feathers tilt so that air can pass through them, lessening drag. On the down stroke, the larger vane of the trailing edge bends upward, pushing down the leading edge. Each feather performs like a propeller with every wing stroke. In addition, with every stroke, the wing is positioned either slightly forward or backward, not just up and down.

Feathers give the wing its shape and there is a direct correlation between its form and function. Birds who fly fast in open air have long, narrow wings. They have difficulty in taking off, but can stay in the air indefinitely, once airbone. Woodland birds must fly slowly to manoeuver between branches and trees, as well as take off frequently. These birds have short, broad wings and wide feathers. They cannot fly as fast or as long as birds with longer, streamlined wings. Finally, birds that soar have broad secondary flight feathers, which greatly increase the surface area of the wings so they can ride easily on the warm air currents.

The last type of feathers which plays a vital role during flight is on the bird's tail. The tail acts as the rudder, balancing and streering the bird. The tail feathers have vanes of equal size and can be tipped in different directions for stability. While soaring, the tail feathers are spread to increase the surface area and get more lift. The entire tail can be twisted to change direction. and to aid the bird when stopping, the tail is turned downward and acts like a brake.

2.3 The muscles

The biggest muscles a bird needs are its flight muscles. These are highly developed because they must raise the entire body weight into the air. A man's chest muscles equal 1% of his body weight, whereas in birds it is 15% of the body weight. The major and minor pectorals of a bord move its wings. Very little muscle is found in the wing itself, for that would add weight and make the wing even more difficult to move. Instead, bird's muscles are in the chest and are attached to the wings by large tendons. The major pectoral muscles attach to the under side of the wing bone. The minor pectoral muscles attach to the top of the wing bone by a long tendon that passes over the shoulder like a rope over a pulley (see figure 1 and 5). However, not all muscles in birds are used for flight. Most birds also walk, hop or swim, so they also have well developed leg muscles.

2.4 Navigation and Flight control system

The brains of birds are smaller than those of most mammals. They live in a world of sight and sound so those areas of the brain are most highly developed. The visual and locomotor area must be capable of transmitting nerve impulses very quickly because birds fly at high speeds. They must judge distance accurately to make landings, catch insects and other prey, distinguish colors (day hunters), see in dim light (night hunters), and see from great distance (high-flying- birds). Consequently, a bird's brain is significantly more developed in the area of vision than in any other area. The occipital lobe and the eyes fill most of a bird's skull. Some birds even have eyes that are so large that they weigh more than their brain!

Most birds have eyes placed on the sides of their heads. This greatly increases their field of vision. However, because the eyes are fixed they must turn their heads to see more. Birds have very flexible necks. The structure of their eyes is also unique. Birds have three eyelids. There is an upper lid like humans have. There is also a lower lid, which is usually closed when sleeping. The third lid sweeps horizontally across the eye cleaning it like a windshield wiper. It may also protect the eye against wind while flying. In diving birds it acts like an extra lens. Hawks and owls may be able to bend this third lid like a lens, giving them the same effect as a zoom lens on a camera.

Hearing is another sense that is well developed in birds. The ears not only hear well but are also responsible for maintaining balance. This is of critical importance during flight. The cerebellum, the muscular control area of the brain, is also extraordinarily well developed. As flying is a complicated series of muscular movements, the brain too develops accordingly. The fast sensory system is able to detect deviations during flight such as gusts, turbulence etc., and provide the assessment for avoiding obstacles etc. Contol of pitching, rolling and yawing are accomplished by the movements of the tail and wings–sometimes differential changes, sometime coordinated and also through changes in the flapping modes of the wings i.e. unequal beat frequencies and amplitudes.

3. Types of Bird Flight

Although practically every bird species seems to have some specific features. It is easily observed that, broadly speking, there are five types of flight.

- flapping flight
- hovering flight
- gliding flight.
- soaring flight
- take-off and landing

Figures (6) and (8) depict these types in summary form. Every bird flaps its wings in (what generally appears to be) an up-and-down repetitive fashion. Some birds flap continuously throughout their flight. Others may, after attaining adequate speed and altitude, stop the flapping motion and glide like sail planes on their outstretched wings, flapping again when required. Yet others may alternate between flapping and gliding - "bounding" like some kingfishers and small birds.

3.1 Flapping flight - "power-on"

This can be regarded as "power-on" flight since the bird continously expends energy in flapping its wings and genertes the thrust and the lift forces to propel it and overcome gravity. Careful observation shows that while the general manner of wing flapping motions may appear similar in all birds, there are many subtle differences between these motions in small and large birds. The motion of the flexible wings is not only in the up-and-down direction but there are also forward and backward components, and parts of the wings twist during the flapping cycle.

Detailed studies show that the wings perform a dual function, working both as airfoils and propellers. Lift and propulsion are effected by a complex combination of vertical and horizontal motions along with bending and twisting of wings during the flapping cycle. During flapping flight one can distinguish two distinct movements of the wing. The first is the 'downstroke', or the power stroke, during which the wing generally moves downwards with the outer and faster moving part also moving forward, especially towards the end of the stroke. The second movement - the 'upstroke' - essentially restores the wing to the fully up position from which the downstroke starts (see figure 7). However, in the upstroke, so as not to produce unnecessary resistance (drag) and lose the lift, the wing goes through a complex bending or the twisting motion. At the end of the downstroke, the wing first rotates upwards from the shoulder while the elbow is relaxed so that the outer wing bends down as well as rotates to present the least resistance to the forward motion. Approximately half way through the upstroke the outer wings are moved up and back at a very rapid rate with outer feathers separated. This action not only reduces the drag but, in some birds, actually provides extra lift and forward thrust.

During the power (down) stroke, the primary feathers are held close together to produce a near perfect airfoil for producing the maximum lift and thrust with minimum drag.

3.2 Hovering flight

The ultimate in low speed flight occurs when the forward speed diminishes to zero, or practically zero, and yet the bird has to be airborne. The classic example of this type of flight are the humming-birds of the American continents which hover stationary in front of flowers while sipping the nectar. The kinematics of hovering flight demand wing movements such that, apart from a vertical reaction, forces are also generated in the horizontal plane. Such hovering usually occurs in a prevailing wind current so that, relative to the bird, there is wind velocity and some lift available, while relative to the observer, the slow forward motion of the bird is neutralized by the wind and the bird appears stationary.

3.3 Gliding and Soaring flight

Gliding flight occurs when the bird does not flap its wings but uses gravity to provide the means for flight. In still air the path of the bird with wings spread is inclined downwards and the combination of the aerodynamic forces generated by the motion through the air and the force of gravity create a balance of forces allowing steady gliding flight.

Soaring takes place when a sliding bird is able to use air currents with vertical velocity components such as thermal, slope currents near mountains, cliffs etc. A particular form of soaring, known as dynamic soaring, can occur only when the wind has a velecity gradient with the speed increasing in the upwards direction (i.e. away from the ground). The most familiar gliding and soaring birds are the vultures and kites. Hankin (1913) observed that birds of different weight and slze followed soaring in succession after sunrise, the heavier ones coming later. He related this observation to the rising up-currents caused by differential heating of the atmosphere by the sun's rays.

3.4 Take-off and Landing

During take-off, the forward speed of the bird being low, the primary requirement of lift to overcome gravity is essentially provided by a fast flapping rate which is higher than in normal forward flight. The amplitude of flapping is also greater. However, landing is even more difficult than take off. Flight must be ended gradually. The heavier the bird the greater its speed and the more difficult the landing. There is a specific sequence for landing (see figure 8). First, the bird slows its wing beats, reducing the forward speed and lift. Next, gravity begins to pull the bird down. Here the tail may be spread open and lowered to act like a brake . The feet are moved forward, ready to grab the branch. To slow it even more, the wings may be cupped like parachutes. The slots are opened to prevent stalling.

4. The Mechanics of Flight in Birds

The basic aerodynamic requirements for sustained flight are :

- enough lift to balance body weight, and
- enough forward thrust to balance backward body drag.

As the wings of birds have to generate both lift (upward force) and thrust (horizontal force), their motions and forces on them which arise due to interaction with the air are much more complex to analyze and quantify than on aircraft. The main aim in applying mechanical principles to bird flight is to relate the forces acting during flight to parameters such as wing dimensions and total weight and arrive at estimates of the power required and speed attained. Knowledge of the aerodynamic parameters often allows appreciation of the difference between types and species of birds.

The amount of lift (L) and drag (D) generated by the motion of a wing through the air depends upon five main factors :

- shape of the wing (cross-section as well as planform);
- angle between the surface of wing and direction of air stream (α);
- area of the wing (S);
- density of the air (ρ) and its kinematic viscosity (ν).
- velocity of the air stream relative to the wind (v)

The relationship between these fators can be expressed as ;

$L=0.5\rho V^2 SC_L$

$D= 0.5\rho V^2 S C_D$,

Where C_L and C_D are non-dimensional co-efficients which depend opon the properties of the airfoil section and Reynolds number (representing the ratio of the dynamical force to the viscous forces).

The distinctive shape of a wing is known as an airfoil. As the arifoil moves through the air, air goes above and below. Lift is created by the movement of the air around the wings (the lift created by the body or tail is small). The shape of the wing is important in generating lift. A bird's wing is "cambered" with its upper surface curved more than its lower surface. Due to its shape the pressure on these surfaces are different. This pressure differential generates the lifting force experienced by the wing. The greater the weight of the object the more lift is needed.

The amount of lift a wing can produce is governed by several factors. One way to increase the lift is to change the angle of the wing as it faces the air. Tilt the leading edge up and the distance the upper air steam must flow is even greater. This is called increasing the angle of attack. The bird changes the angle of the whole wing while a plane lowers the flaps on the trailing edge, but the result is the same. If the angle of attack is too great all lift disappears and the bird or plane begins to fall to the ground. This point is called the stalling point.

There is still another way to get maximum lift without reducing the angle of attack. If the air across the wing can be made to move even faster, thus changing the pressure, which pulls the air stream back down on the wing, then lift will be produced again. This can be accomplished by forcing the air through an even smaller space, or slot, just ahead of the upper surface of the wing. These slots can be formed in a number of ways :

a) In birds there are a few feathers attached to a movable finger bone like our thumb. It is called the alula and it is on the front of each wing. The bird can easily adjust this slot to increase lift.

b) Birds can also manipulate the feathers at their wing tips to produce slots if necessary.

c) Birds can also raise the feathers on the leading edge of the wing to form slots.

Speed is the most important element in producing lift. However, speed can be increased by increasing the forward speed of the wing itself as it travels through the air. This causes an even more dramatic change in lift. If you double the speed, you get 4 times the lift. Triple the speed and you get 9 times the lift as is revealed from the equation given in § 4.

The weight of the bird determines how much lift is necessary. Contributing to this is whether the bird is going up, down or in level flight. Going up, lift must be greater than weight; in level flight, lift must equal weight; and going down, lift is less than weight. Therefore, birds with large wings get lots of lift at slow speeds, but birds with small wings must move faster before they become airborne. Minimum speed for lift is dependent upon the design of the bird.

Most birds must be moving forward through the air in order to get lift. So, how do birds create forward motion? in propeller planes, air is pushed backward as the propeller spins. In jet-planes, air is forced through the engines and out the back. In birds, it is the flapping of their wings that produces the forward motion called thrust. But how does the up and down motion of wings push the bird forward? One would think the downward flap might push the bird up, but the upward flap would push it back down again. To understand how a bird produces forward motion, the structure of the wing must be examined.

The structure of the bird's wing is such that it can be folded close to the bird's body when it is not in flight. But when the wing is extended, it acts as both wing and propeller. The feathers attached to the "hand" bones are the ones that produce the forward thrust for the bird.

The forward motion of flight is the result of pushing backward. When a person walks forward, he pushes off the ground. Rowing a boat forward requires pushing against the water. On a bird, the primary flight feathers are what pushes backward against the air. On the downstroke they push backward against the air. Then the feathers twist in such a way they push air backward on the upstroke too. The feathers twist back and forth as the wing goes up and down. Flight feathers in the tail, with a central shaft position, do not twist.

The twisting is automatic and is caused by the unequal size of the vanes. The larger vane bumps into more air than the smaller one. On the upstroke, more air hits the top of the larger vane; so this part is pushed down. On the downstroke, again the air pressure is greater on the larger vane but this time is pushes it up, twisting the feather in the opposite direction. Thus, as the wing flaps up and down, the feathers twist back and forth. Only the primary and secondary feathers do this.

The primary feathers at the tip of the wing are the most important. First, they travel the furthest distance. They are spaced so they don't interfere with each other when twisting. They are stiffer than the other feathers. Their barbs are thicker near the base, which gives them an airfoil shape. They also twist back and forth, but it is primary feathers that give the bird its main forward thrust.

5. Effects of Size and Shape

During the evolutionary processes of the birds, three main kinds of morphological changes have taken place.

◆ The wings of birds have lengthened. The area swept during flapping has incresed thus lowering the induced power to manageable levels at low speeds.

◆ The muscular system has become modified in such a way as to transit large amounts of power to the wings.

◆ The body has become streamlined for drag reduction.

Bird flight has two major areas of complexity. The first derives from the fact that flight provides the bird an extended range of means for its life and development. Many different modes of flight are used. These include straight and level flight, climbing. diving, bounding, soaring, take-off and landing, hovering and manoeuvres such as zig-zagging etc. The other area of complexity arises from the highly non-linear interaction between a bird's flight activities, which generates lift for weight support and propulsion for overcoming drag. Various researchers have attempted similarity analysis and scaling laws to relate flights of different types for birds. However, due to limited scope, it is not discussed here in detail.

6. Conclusion

Flight is much more than just feathers and wings. Everything about a bird is perfectly designed for flying. Modern birds are structurally and functionally efficient because they must be able to take flight, stay aloft, and reach their destination under many diverse condions. Their skeletal, muscular, nervous, circulatory, respiratory, degestive, and even reproductive systems have been designed for flight. All systems must exhibit maximum power and efficiency with a minimum of weight. The key factor in adaptations for flight is lightness. A compact streamlined body combines strength with lightness and a versatile musculature controlling the unique feather-covered wings provides the bird with an unequalled system for flight.

The flying of bird involves a lot of aerodynamic theories and their direct application. But here an attempt has been made to describe some general features of bird's flight-the flight apparatus of the bird and the modilities of flight for even a non-professional. Cumbersome equations and difficult theories behind the subject have been intentionally omitted in order to present the topic in a lucid manner.

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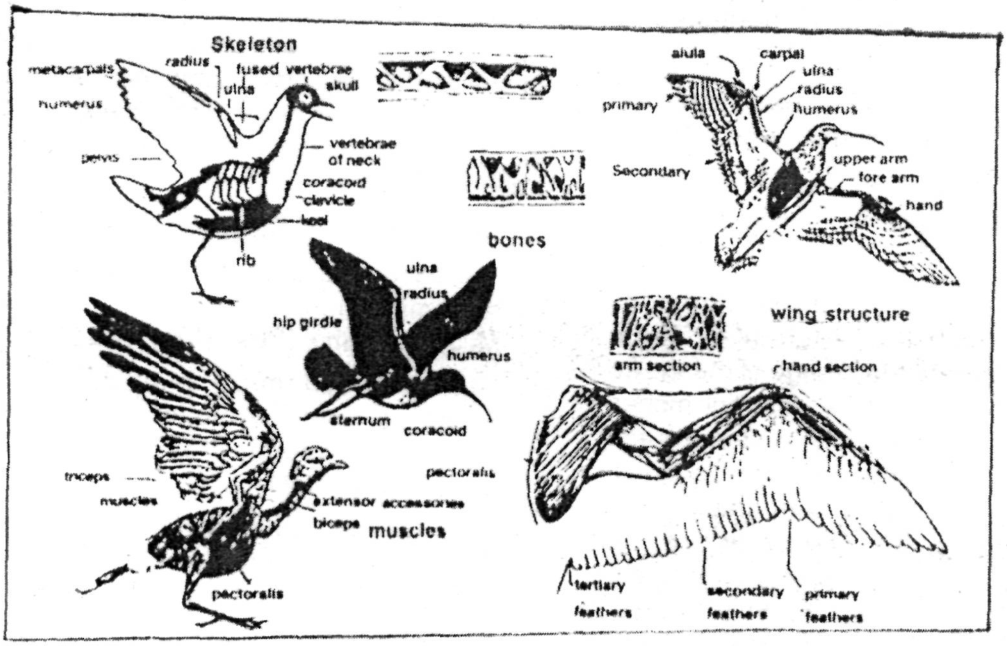

Figure 1. Framework for flying. This figure is compiled from figures taken from Dalton (1977 pp 74. 75 & 79). Ward-Smith (1984. p 69) and Ardley (1984. pp 4 & 6)

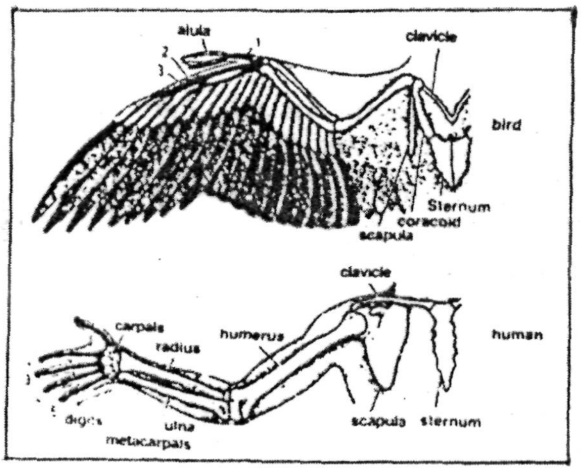

Figure 2. Bird wing and human arm.

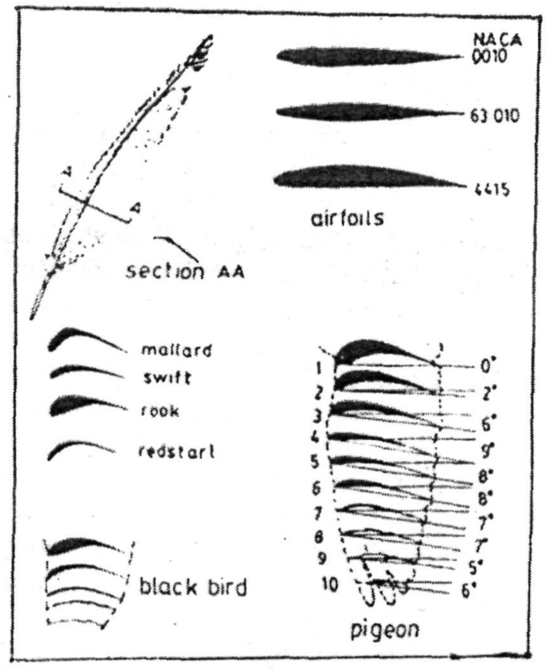

Figure 3. Wing profiles (adapted from Ward-Smith 1984. p 74.)

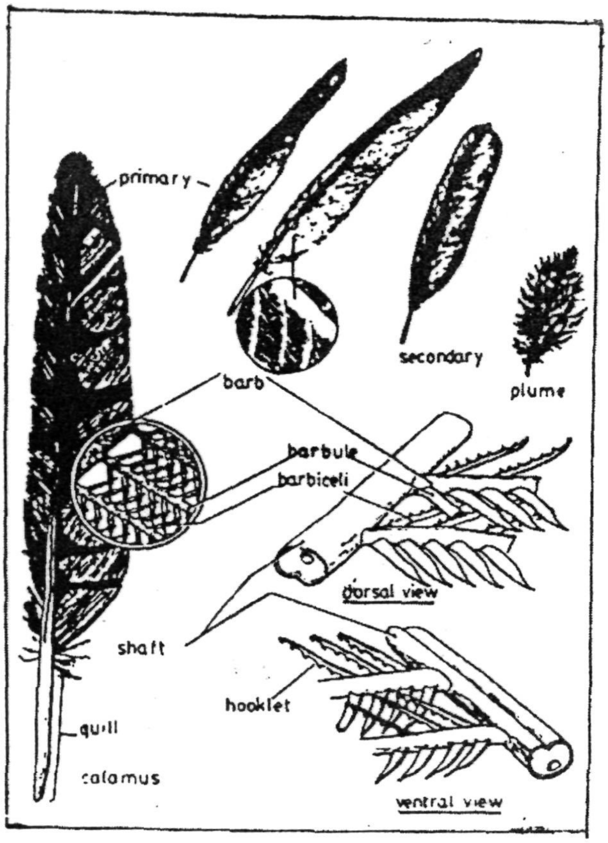

Figure 4. Structures of feathers (Adapted from Freethy 1982. p. 69)

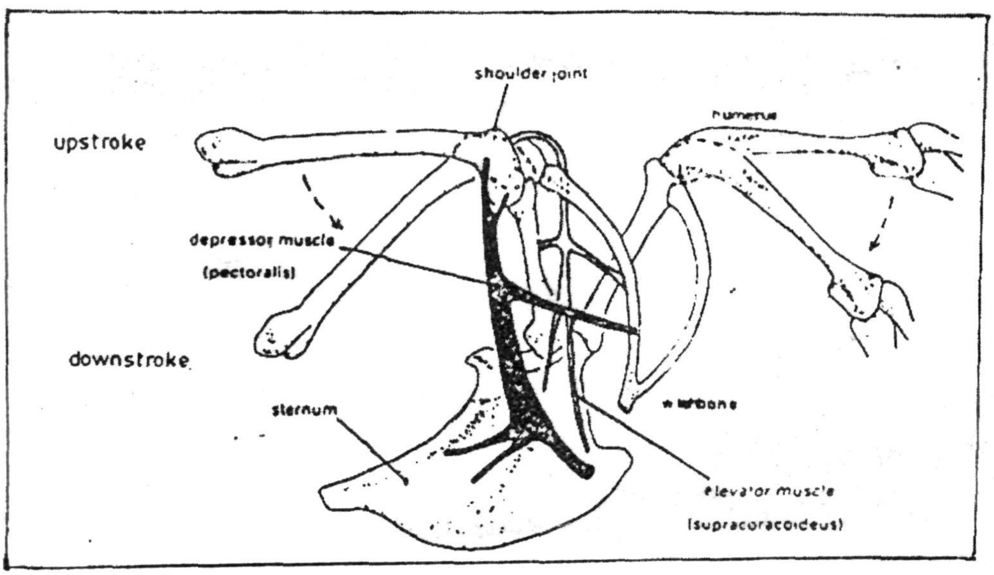

Figure 5. Muscle action (From Freethy 1982. p. 65)

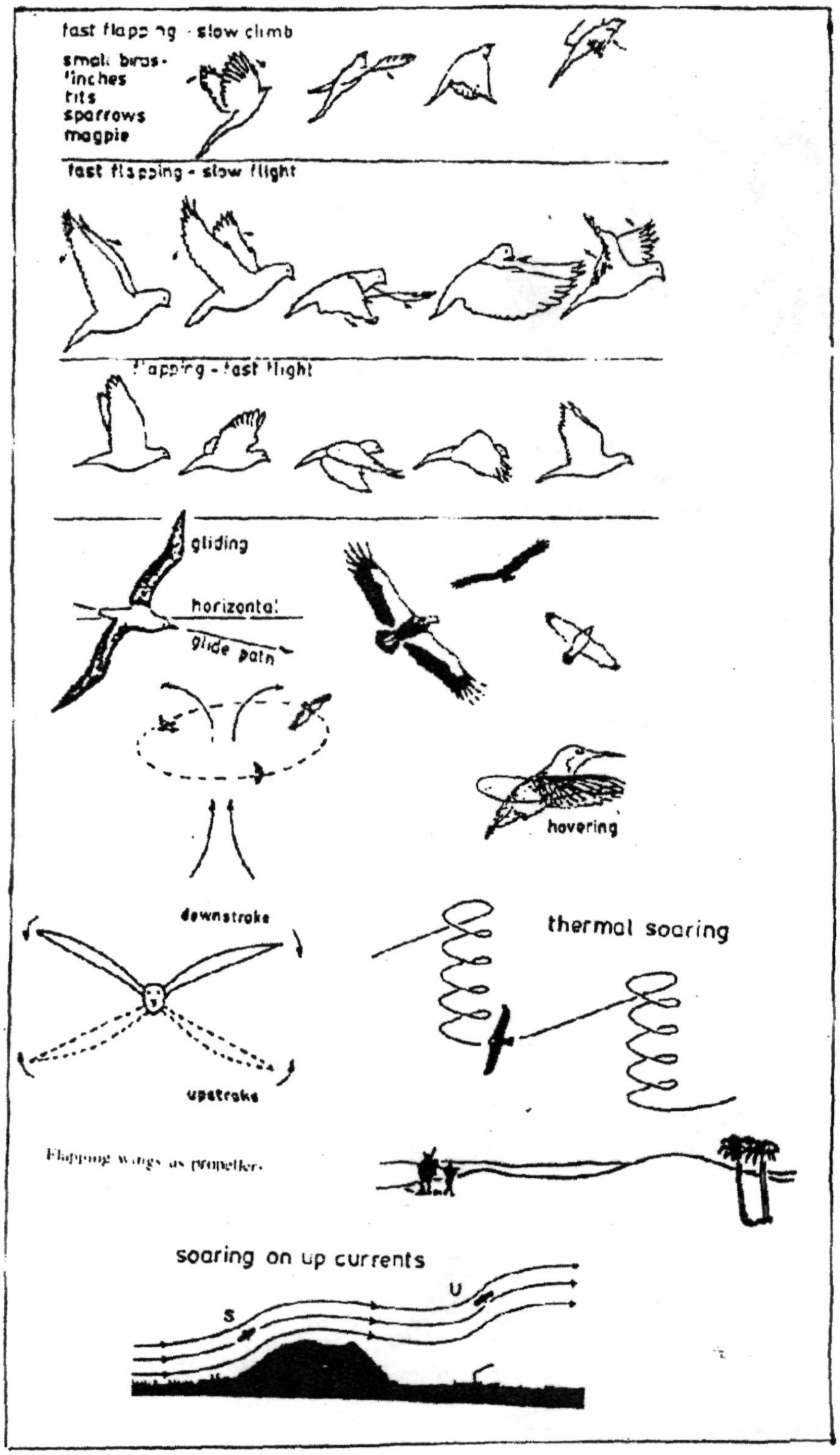

Figure 6. Types of bird flight (From Brown 1963)

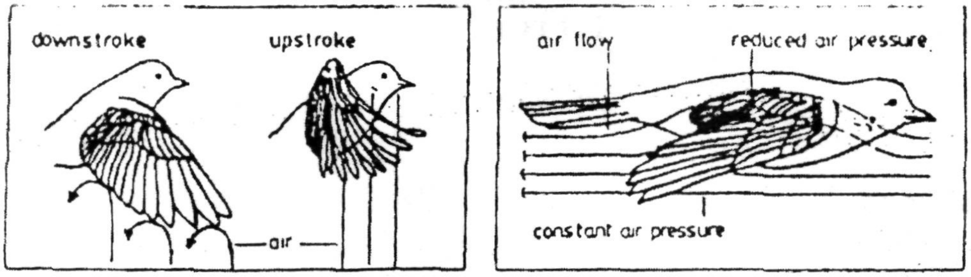

Figure 7. Wing attitudes in flight. (From *World Book Encyclopedia.* p. 287)

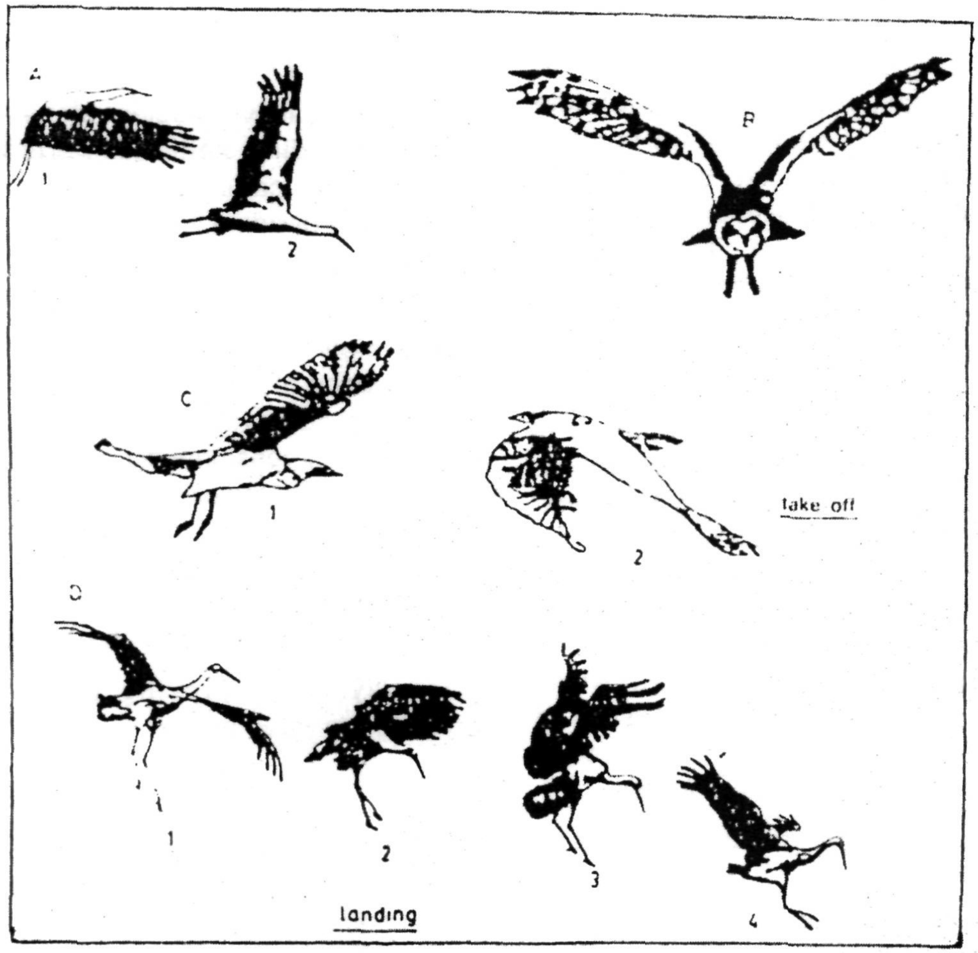

Figure 8. Take-off and landing of large birds. (A) Stork take-off (1-wing pulled torward on downstroke; 2-end of upstroke). (B) Owl upstoke after take-off. (C) Take-off of large heron (1-downstroke beginning, 2 - downstroke end with outer wing pulled forward and twisted). (D) Stork landing (1 - steep glide with alulae raised and wings extended. 3 - braking wing beats; 4 - landing on nest). (From Ruppell 1977. pp. 64, 65, 80 & 81)