# Natural and Artificial Flying Machines

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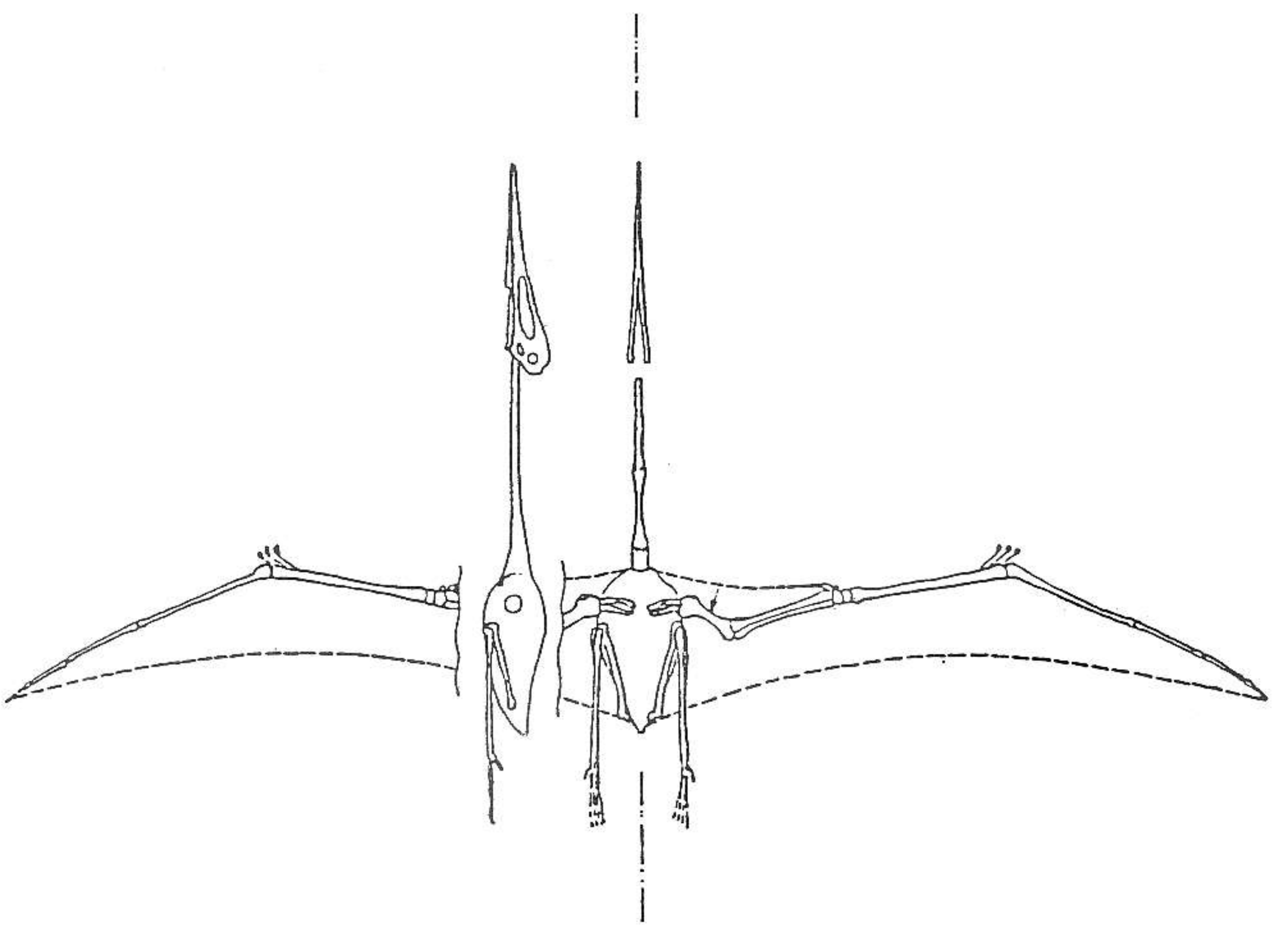


## SUMMARY

The advent of fossil fuel engines offered aeronautical engineers ten-fold to hundred-fold increases in power-to-gross-weight ratios over the ratios available for biologically powered flight creations such as birds and human powered aircraft. The tremendous achievements of engine-powered aircraft over the past eight decades have tended to obscure how numerous flight problems had already been elegantly solved by birds, many tens of millions of years ago. Recent projects in human-powered aircraft, in bird aerodynamics and in the development of a flying replica of an 11-meter span pterodactyl have introduced us to the bird-airplane interface. The result has been an increasing respect for "Mother Nature the Engineer," who derived elegant and satisfactory evolutionary solutions for all the factors involved in biological flight. In many respects, engineers and scientists still have much to learn from nature regarding aeroelasticity employed to tailor structures to the varied demands of flight, active control technology, boundary layer control, navigation, etc.


## INTRODUCTION

Early aviation inspiration arose primarily from the role model of birds, with some early flight attempts even involving feather substitutes and bird shapes. After the successes of Cayley, Lilienthal and the Wrights, and the growth of the theoretical underpinnings of the field by Lancaster and Prandtl, man's aviation constructions raced far beyond those bird ancestors and the role model became virtually forgotten. Everyone still observes birds and admires their grace, beauty and freedom, but their role in aviation has been relegated more to worries about avoiding ingesting them into jet engines or cleaning their messages off wings than to considering them as creatures offering useful insights to designers.

There is still increasing basic research about birds and their evolution, but if we recognize a connection at all to aircraft, the connection is likely to be only the after-the-fact realization that a modern design solution could have been foretold by observing how nature has been doing it for millions of years. Using nature's designing to help us solve new aeronautical problems is rare. Perhaps the appreciation for evolution as a master designer of aeronautical form and function best suits the sailplane field. Sailplanes, like soaring birds, must be very efficient and must be operated efficiently to utilize nature's invisible lift and so sailplane pilots and designers still observe birds carefully and learn something from them.

Considerable literature exists about natural flight. For general reviews, see the Symposium on Flying and Swimming in Nature (1975), Kuethe (1975), and McMasters (1984), each of which has helpful reference lists. The latter two also make many comparisons of natural and artificial flying devices. The focus of the present paper is on selected items not covered in these documents, but overlap is unavoidable.

Circumstances have involved me with the interface between natural flight (birds, pterosaurs, insects, etc.) and artificial flight (airplanes). The explorations have been stimulated especially through the subject of human powered flight wherein natural muscle is integrated with artificial structure and mechanisms. The explorations have emphasized low power loadings, a focus related to the inefficiency of muscle compared to internal combustion engines. The explorations have thus also emphasized aerodynamic efficiency and light-weight structures, which permit flight with lower power loadings.

The outcome from all this for me has been a growing realization that Mother Nature is a fantastic aeronautical engineer, and has been so for many tens of millions of years. Nature utilizes evolution to develop solutions for filling ecological niches. There are continuing variations of creatures and continuing survival pressures. Statistically, only winners survive to leave progeny. In contrast to scientific developments in civilization, mistakes tend not to be respected as learning experiences, and second chances are rare. Uncompleted "projects" in nature cannot be rescued by a sponsor picking up overrun costs. A bird has solved myriads of problems in aerodynamics and structures, including problems scientists have not even recognized yet. Identifying and investigating these solutions provide fertile research opportunities.

## SOME BACKGROUND FACTORS AND PERSPECTIVES

There have been a number of events and projects which served to stimulate my enthusiasm for nature's engineering of flight devices. A brief review here of these events and projects will set the stage for the comparisons of natural versus artificial aeronautics devices which follow, with the review illuminating some key points.

In the late 1930's, my hobby of model airplane flying introduced to me the comparison of man's constructions with birds, and an appreciation for the effectiveness of birds in locating and using thermals. From 1945 to 1956, a commitment to sailplanes and soaring, as scientific research topics, further fanned my interest in and awe for the flight of soaring birds. A paper by Woodcock (1942) titled "Soaring Over the Open Ocean," made a deep impression on me because it seemed to be an ideal sort of scientific experiment, one which had significance and yet could be conducted without any special equipment. He watched soaring birds during a long ocean voyage; saw whether they soared in circles, straight lines, or did not soar at all; noted the wind speed and temperature difference between air and water; and found that the atmospheric flow patterns indicated by the soaring techniques for the various winds and stabilities were analogous to the patterns of Benard cells in liquids which had been studied in laboratories and for which quantitative theory was well developed. Thus motions on scales of millimeters in laboratory liquids (involving molecular transfers) were related to motions at a millionfold scale increase in the atmosphere (involving turbulent eddy transfer), with bird observations providing the key data link.

Somehow, advancing science by watching birds soaring seemed an elegant research technique. In 1976, on a rare family vacation driving across the U.S., I realized that certain simple observations of birds in circling flight could provide valuable information on their aerodynamic capabilities. In fact, even the in-flight average lift coefficient of the airfoil could be inferred. The vacationing study had two fruitful outcomes, beyond an initial informal paper (MacCready, 1976). For one, my comparison of flight characteristics between birds of different species and hang gliders and sailplanes served as the catalyst for the idea behind developing the Gossamer Condor (see MacCready, 1978, 1979; Burke, 1980; Grosser, 1981; and Nova, 1983). The other outcome was a more careful investigation in 1980 and 1982 into the flight characteristics of frigate birds, possibly the best of all natural soarers (MacCready, 1984). This latter study suggested that a) frigate birds may sometimes operate at a surprisingly high lift coefficient, higher than we would have expected at the operative Reynolds number, and b) the birds significantly altered the details of their thermaling flight mode with the meteorological conditions, as do sailplane pilots.

Our human-powered airplane projects (Gossamer Condor, 1976-77; Gossamer Albatross, 1978-79; Bionic Bat, 1984-85) focused our attentions on the interrelation between birds and airplanes. Henry Kremer's prize challenge was to use human power to fly. A human has a low power-to-weight ratio, but it is probably not greatly dissimilar to that of a soaring bird. In any case, the power-to-vehicle gross weight ratios for the biologically powered vehicles are about two orders of magnitude less than the ratios for aircraft powered by internal combustion engines. The low power-to-weight ratio is compatible with flight at a low wing loading and hence at low speed.

Attention to low speed flight stimulates attention to the effects of atmospheric turbulence on efficiency and controllability. Performance of the Gossamer aircraft deteriorated rapidly with increasing turbulence. At a flight speed of only five or six meters per second a gentle localized upcurrent or downcurrent of 0.5 m/s means a local angle of attack change of about 5° with consequent negative effects on induced drag and parasite drag. The effects on stability can be even more significant, as the effective angles of attack on surfaces exceed stall limits and the control limits of ailerons. Extreme care had to be exercised in flying our solar powered Solar Challenger at about 10 m/s in turbulence near the ground. Similarly, operating hang gliders near the ground, at comparable speeds, emphasizes control limitations in turbulence. Birds have the brains and muscles to articulate their wings as dictated by the local airflow, and hence fly without problems in the turbulent conditions which trouble these piloted aircraft.

Finally, my growing respect for and envy of nature as a designer of aeronautical creatures got another boost recently as a consequence of my starting on a project to recreate a flying replica of a giant (11-meter wingspan) pterodactyl. Not only did the size go well beyond the limit size of a natural flying creature as designed from extrapolation by standard scaling laws, but the tailless flier likely had a wing which was unstable in pitch and so the pterodactyl must have used some manner of active control (wing sweep?) to provide effective stability. A hunt for literature on bird pitch stability and controllability was generally unfruitful. Analogous birds such as the albatross, gannet, and even sea gulls, in smooth slow gliding employ essentially no tails; their active control system deserves study.

Starting with this background, it seemed reasonable to explore broadly just what flight-related features nature may have developed prior to civilization's technological aeronautical developments.

## OVERVIEW OF NATURE VS. ARTIFICIAL FLIGHT AND FLIERS

There are several major factors where birds (or other natural fliers) cannot be expected to be directly analogous to airplanes. One is in transonic and supersonic flight, which is certainly only man's prerogative (natural flight evolution was never concerned with aerodynamic effects of the speed of sound). Another factor is the power system. The high energy density, and especially the high power-to-weight ratio, obtainable with fossil fuel let airplanes achieve speeds, altitudes and load carrying capacities which are beyond consideration for birds. For the most part, the best direct correlations between natural and artificial fliers should arise from the larger natural fliers vs. the smaller and slower airplanes.

An obvious difference between birds and aircraft is that propulsion in birds comes from flapping wings while in an airplane it comes from rotating machinery (propellers, either exterior to or integral with the engine). But for each propulsion method the mechanical-aerodynamic propulsion efficiency during normal flight is usually within ± 10% of 85%. Thus the one method does not offer any great advantage over the other for propelling the vehicle.

The bird offers great features of versatility. For example, auklets, water ouzels and cormorants are effective in flying through the air, walking on the ground, and operating on and under the water. No doubt a manned airplane could be constructed to do the same, but the undertaking would be formidable.

A bird's versatility is to some extent associated with the use of parts for multiple functions. For example, a bird's wings are for propulsion, lift, and stability/control with variable geometry for various flight modes; also they serve for ornamentation, and for insulation when retracted. With an airplane the function of each part tends to be more specialized. For the ultimate in efficiency (the sailplane with a best glide ratio exceeding 60:1) the separation of function is distinct. The wing handles lift efficiently (and roll control), the fuselage handles the payload (and supports the landing gear and tail), and the tail provides yaw and pitch stability and control. To use the pitch control device to contribute to lift (a canard), or ask the wing to handle the stabilizer/elevator task (a flying wing) compromises vehicle efficiency even though it may offer benefits in other areas. For an airplane, the total flight system can be modified to permit emphasis on efficiency where it is needed. A long runway permits an airliner's design to emphasize cruise efficiency; if a birdlike takeoff from a tree or from unimproved ground were required, the vehicle would be more like a helicopter or Harrier jet, with much lower cruise efficiency and payload capability.

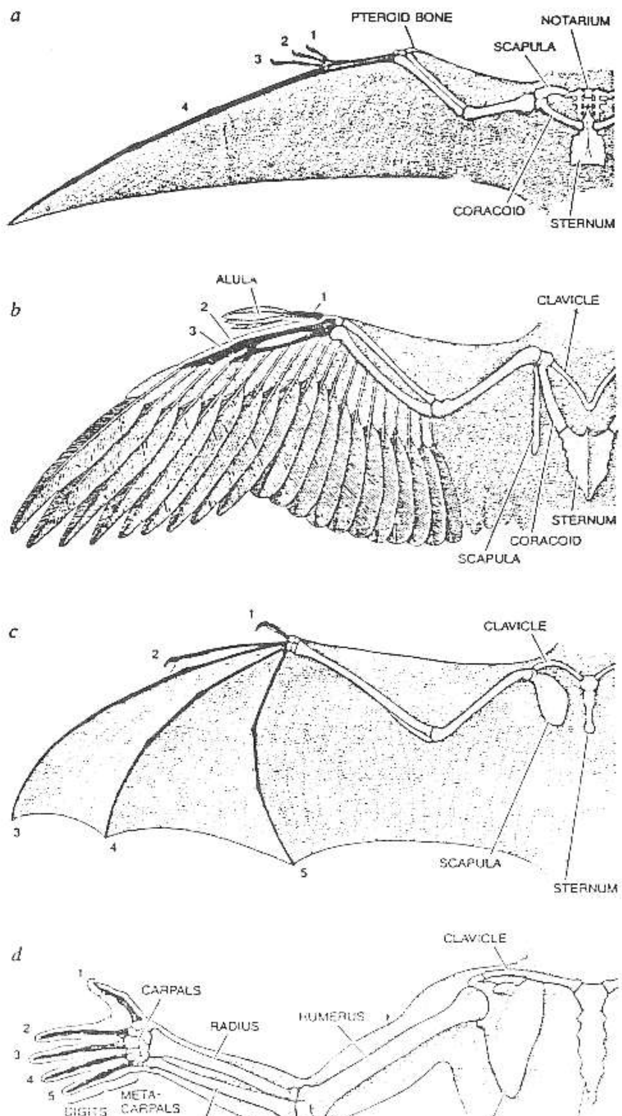
Nature has evolved full flight by at least four separate routes: birds, mammals (bats), reptiles (pterosaurs) and insects. For more limited flight we can even include flying fish, gliding mammals and seeds. When filling a particular ecological niche, say involving a flying animal of about one meter wingspan, the rules of conservation of energy and momentum, the realities of viscous flow phenomena and the limits of biological power and biological structure dictate that nature finds rather similar solutions no matter what the starting point. **Figure 1** illustrates the different skeletal solutions by reptiles, birds and bats for producing a wing. Where birds and insects overlap, as with a hummingbird and a hawk moth (hummingbird moth), the appearance and function, both for flight and for feeding on a flower's nectar, are remarkably similar, but the inner structural details are quite different.

Human engineers face the same aerodynamic realities of energy, momentum and viscosity as do flying animals, but the engineer can utilize structure strength-to-weight and propulsion power-to-weight efficiencies which are many times those available to biological devices.

### BIRDS VS. AIRPLANES

A. Long flights

Aircraft, with air-breathing engines, have stayed aloft 84 hours and covered almost half the circumference of the earth without aerial refueling. With refueling, the duration rises to 64 days, and distance to more than around-the-world. Birds hold their own in the duration and distance categories.




WINGS of a pterosaur (a), a bird (b) and a bat (c) are evolutionary variations on a forelimb that was suitable for an earthbound animal that walked on all fours. The variations are distinctive: in the pterosaur it is the fourth finger that supports the wing; in the bird it is mainly the second, and in the bat it is the second through the fifth. In each animal the wing attaches to the trunk by means of the shoulder girdle, a ring of bones. The girdle of the larger pterodactyls is peculiar in that the scapula, or shoulder blade, turns inward and abuts the notarium, a unique pterosaurian bone, at the midplane of the body. The notarium is several vertebrae fused together. The arrangement provided a base for the action of the wing. The arm of man is shown in *d*.

Figure 1
Arms and Fingers Into Wings.
This is a figure provided by Langston (1981).

1) The sooty tern can stay aloft for years at a time. Of course it uses aerial refueling, primarily to snatch food (fish and squid) from the ocean surface without alighting.
2) The Arctic tern migrates from the Arctic to the Antarctic, covering thousands of miles between landfalls and staying aloft days and weeks at a time.
3) The ruby-throated hummingbird migrates from Florida to Central America across the Gulf of Mexico.
4) Some swifts stay aloft day and night.

B. High flights

Aircraft can exceed 80,000-foot altitudes. Birds can't compete. Eagles have been seen higher than 30,000 feet, but birds' sustenance arises only from locations on the ground or near the ground, and there has been little evolutionary pressure on high altitude flight.

C. Navigation

Aircraft navigate over long distances using dead reckoning, the magnetic compass, many radio aids, and even inertial navigation.

Birds home over considerable distances, and also navigate effectively during long-distance migrations. They apparently use a variety of clues and senses, including visual geographic landmarks, celestial objects, sky polarization and magnetic fields. Most amazing, some migrations are conducted without the bird having experience for the particular flight. The destination is genetically pre-programmed into the bird's brain; this can be considered the equivalent of the navigation of a cruise missile, except doing the brain job with less material but more versatility.

It has been reported that birds do weather forecasting, to pick the right phase of a meteorological pressure system which will provide the tailwinds needed to make the migration possible.

Some birds use echo-location over short distances, and of course most bats do. This is the acoustic equivalent of radar.

D. Flight maneuvers

Aircraft sometimes are flown in formation, perform aerobatics and engage in dogfights.

Birds do the same. The formation flying of ducks and geese saves energy and probably serves some social communication function. Some birds seem to do aerobatics just for the fun of it. I have observed a raven doing fast rolls which had no obvious relation to saving energy or acquiring food. I watched a frigate bird climb to cloud base in a thermal, far too high to seek food, then tumble to low altitude like a flopping, limp rag, an inelegant descent mode which looked like "just for the fun of it."

In East Africa the Bateleur eagle, with a minuscule tail, will intentionally somersault in flight. As to aerial dogfights, these are common. Hawks will fight each other, and attack prey in the air as well as swooping down to ground-based prey. Small birds fight off hawks to protect territory.

When it comes to birds, bats and large insects catching small insects in flight, the detection and maneuvering on both sides resemble aerial combat with aircraft. There are stealth techniques, camouflage, countermeasures and communications.

E. Aerodynamics: airfoils

As airfoils have been evolved by human engineering over the past hundred years, there have been huge improvements in understanding and controlling boundary layers, increasing lift, decreasing drag and improving pitching moments. Man has refined geometry; added slats; provided flaps and slots and multi-element airfoils; installed boundary layer trippers, vortex generators and fences; applied spoilers; and utilized variable geometry to adapt a configuration to varying conditions.

Birds have engineered all of the same airfoil features, as needed for the Reynolds numbers of 10,000 to 200,000 at which their flying surfaces generally operate. When it comes to the lower ranges of Reynolds numbers, the birds' solutions may be better than man's. The frigate bird tests cited earlier suggested that a $C_L \sim 1.8$ was achievable at a Reynolds number of about 50,000. Pennycuick (1971, 1975) for a vulture and Tucker and Parrott (1970) for a falcon suggest $C_L = 1.6$ is likely obtainable, but the measurements are not definitive. Pennycuick (1983) computed, for slope soaring birds, $C_L = 1.63$ for frigate birds and 1.57 for black vultures. Eggleston and Surry (1980) made wind tunnel tests on computer-designed airfoils for model airplanes and for several found $C_L$ reaching 1.6 for Reynolds numbers in the range 34,000-50,000, with the highest $C_L>$ being 1.76 at Re=36,000. Carmichael (1981) and Pressnell and Bakin (1982) show the influence of boundary layer trippers and invigorators on maximum $C_L$, and even present experimental $C_L = 1.7$ for an airfoil at a Reynolds number of 30,000. Dilly (1981) cites maximum $C_L$'s reaching 1.8 (with very high drag) at Reynolds numbers up to 60,000. Carmichael shows the wide variations in measured characteristics in different wind tunnels. Thus the observations on maximum $C_L$ for both birds and artificial wings at these Reynolds numbers are not definitive, but the data suggest that nature's designs can be as good as the best of man's.

The cross-section of a vulture's primary feather, shown in **Figure 2**, shows a very sharp leading edge. Wainfan (1984) has investigated how the design of effective airfoils varies with Reynolds numbers, and concludes the leading edge radius should be less than 0.25% of the chord at Re=35,000, at which this feather often operates. The observed leading edge fits this criterion. Wainfan notes:

> "Reducing the radius of the leading edge turbulates the boundary layer early and helps keep the flow attached. This effect is enhanced if the airfoil has relatively little curvature in the first 5% or so of the chord aft of the radius. Turbulating the boundary layer by sharpening the leading edge increases the maximum lift of the airfoil and decreases its drag dramatically."

F. Structure

The variable geometry which is readily obtainable with natural wings is the envy of aerodynamicists and structural engineers. The bat's fingers (Fig. 1) can be controlled for violent maneuvers. The primary feathers which are extended and separated at the wingtip of a vulture present, all together, a wide-chord, multiple element airfoil for minimum speed and high maneuverability. In their vertical spread they may

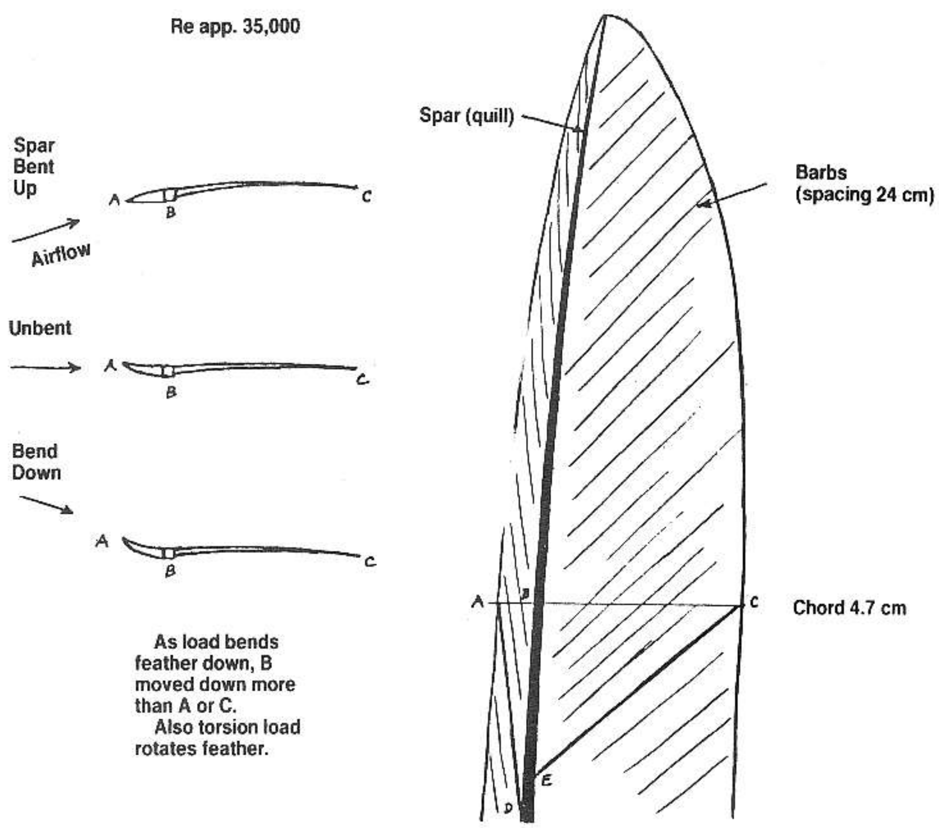



Figure 2
Vulture Primary Airfoil Modification Under Load

also diffuse vorticity and benefit induced drag, in a manner somewhat analogous to winglets.

Examination of one of the primary feathers of a vulture emphasizes the elegance of nature's designing. Fig. 2 shows the airfoil of one of the two front primary feathers which bend up in gliding flight and additionally bend up and down from that position in response to down and up flapping. The tapered rectangular spar cross-section is well tailored to fit within the airfoil shape requirements while giving the desired bending for up and down loads. The location, centered at about 20% chord, provides a twist with lift loads, a load alleviation technique. The feather construction with barbs pointing outward toward the tip serves to vary the airfoil camber with load (Fig. 2). Incidentally, an inadvertent separation of the parallel barbs extending out from the spar or shaft is taken care of perfectly by merely touching the previously adjacent barbs together. Tiny hooked filaments lock into a mesh and the feather is returned to its original condition: Velcro, designed more than 100,000,000 years ago.

The hollow feather spar (quill) construction fits the need for combining strength with lightness. Some bird wing bones are hollow tubes with lightweight internal truss construction to prevent buckling of the thin walls. The wing bones of large pterodactyls are tubes with extremely thin walls, a construction consistent with low wing loadings in spite of the large wing spans. In nature, the wing bones handle all wing torsion, bending and shear loads; the feathers or membranes provide the aerodynamic shape. With the vertebrates, there is no D-tube type construction for handling torsion loads. The exterior would weigh too much. This is analogous to lightweight aircraft: for wing loadings under 10 $kg/m^2$, the spar (and perhaps associated struts or wires) handles all the main loads, with an airfoil shape as a surrounding "glove" (for example, the Solar Challenger, see MacCready et al, 1984). Higher wing loadings usually are associated with stressed skin construction to handle torsion.

The variable geometry of birds' wings and tails permits the configuration to be adapted to the needs, both by muscle and by aeroelastic effects. The innate sensing system and brain also tell the muscles how to alter the configuration. Thus the bird can readily adjust to strong turbulence during landing. A rigid wing airplane cannot; the airflow angles can vary beyond those which can be handled by slats and flaps and ailerons. There have been various attempts with aircraft to use twisting portions of wings. For example, for the Guggenheim Safe Airplane Competition in 1929, the Curtiss Tanager used floating ailerons to achieve controllability even beyond the stall of the fixed biplane wings. The technique worked. A review of the subject and a modern variation are presented by Jones (1984). In 1983 we tested a model glider in which the outer half of each wing was automatically rotated in pitch by an attached tail to maintain a specific $C_L$. With a roll rate controlled servo providing the "brain," the model functioned in turbulence satisfactorily.

Natural wings of vertebrates all fold for maneuvering on the ground, analogous to the folding of wings on carrier aircraft.

A final great structural feature of birds is the retractable landing gear, which is well adapted to rough field operation.

G. Instrumentation

In addition to the sensing techniques required for navigation, birds have the ability to monitor flight conditions in ways analogous to airplane instrumentation. They certainly observe attitude and altitude and speed. They are masters at locating thermals and moving to the strongest portion. The methods by which they find and use thermals are not understood, except that sometimes one bird will observe another catching a thermal and will fly over to use the same thermal (as sailplanes use other sailplanes as thermal indicators, and occasionally sailplanes use birds, and birds use sailplanes). Birds' "instrumentation" demonstrates remarkable effectiveness as a hawk or vulture cruises kilometer after kilometer at 20 meters above the trees, without wing flapping, but with a great deal of maneuvering to translate turbulent ups and downs into sustaining lift. The "instrumentation" also is remarkable as it permits birds to grab insects and other objects out of the air, to swoop down to the ground or water surface to snatch a mouse or minnow, or in the case of the pelican, to plunge accurately into the water to catch a below-surface fish. The biological flier also certainly has the ability to monitor "engine" temperature, and assess the amount of "fuel" on board. The visual acuity of hawks is legendary, for finding prey. Vision may be one key to the sensitive rate-of-climb indicator which a bird must have for assessing upcurrent details, establishing relative height by parallax as the bird moves along its flight path, but this cannot be the explanation for a frigate bird finding lift in a gentle convective cell over a featureless sea.

H. Stability

As with all animals, birds have effective active control systems. For an extremely efficient soarer such as the albatross or gannet, during normal flight there is effectively no tail (the body is simply a streamlined low-drag shape), and yet probably the undercambered wing has a negative pitching moment and so is unstable. Small forward and backward movements of the wing may provide an active control method to produce stable flight. Pennycuick and Webbe (1959) report that "moulting fulmars can fly and maneuver at normal and high speeds just as well without a tail," and ascribe pitch control to fore and aft movements of the wings.

During transient maneuvers of taking off, landing, evading predators and collecting food on the wing, complex control is manifested involving large motions of wings and tail, and even body and legs. In a moderate wind, some birds (especially small hawks) are seen to remain in an accurately fixed position relative to the ground. Movies of such flight suggest the head and eyes can remain rigidly positioned with an accuracy of a millimeter or so, even while the rest of the bird is moved violently about. The head is thus an elegantly stabilized platform. Flying creatures do not have vertical fins and rudders. The wings can be controlled to provide the yaw forces, and in some birds the horizontal tail, with lift on it, is rotated on a longitudinal axis to augment yaw control (as with the Gossamer Condor).

## QUETZALCOATLUS NORTHROPI (QN®)

In late 1983 I felt that advances in composite construction, robotics, stability and control, sensors and servos, and theory of oscillating airfoils had reached the point where one could make a full-scale, radio-controlled, wing-flapping flying replica of the pterodactyl *Quetzalcoatlus Northropi*, the largest natural flier known, with a wingspan of 11 meters. Some flightless birds were much heavier, and the flying Teratorn (a six-million-year-old fossil showed a bird resembling a condor with a 7.5 meter span) was probably somewhat heavier, but this pterodactyl had the largest span. The National Air and Space Museum has sponsored our initial studies of creating the QN® replica.

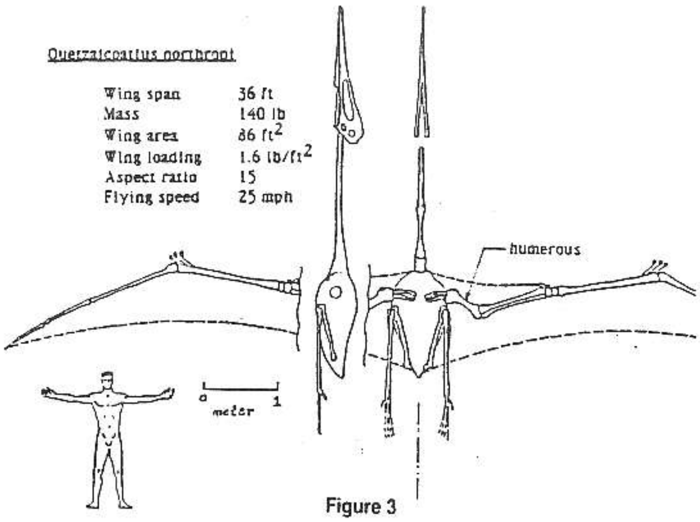



Figure 3

The fossil evidence for this giant pterodactyl is meager and so most details of its shape/appearance require conjecture. The consensus of participants in a 1984 informal workshop at Caltech on the subject was that it resembled somewhat a mixture of an albatross, a frigate bird and a crane, enlarged more that six-fold. **Figure 3** shows the consensus dimensions of *Quetzalcoatlus Northropi*. The next section considers size vs. power questions.

The special problem with this creature is to handle the pitch stability/control challenge of a tailless flier with a cambered membrane wing which probably had a negative pitching moment. Since early 1985 we have been flying a 2½-meter span radio controlled model with swinging-wing control instead of elevator control. We are edging cautiously toward active control based on employing an angle of attack vane and pitch rate gyro as sensors to handle pitch stability when the horizontal stabilizer has been completely removed. As pterosaurs evolved to the larger sizes, for which tails disappeared as efficiency improved, the relative size of the brain increased, presumably partly in response to the increased demands of active control.

Eventual flight of the full-size QN® replica will bring back to the skies a long-extinct flying reptile shape, and will help to interest people in evolution and nature's engineering capabilities. The species did not survive the "great extinction" about 63,000,000 years ago, but nevertheless it probably was a success for much, much longer than man.

## SCALING LAWS

For a flight vehicle of a specific shape but varying size (say defined by span, b,) and varying weight W, if we ignore Reynolds number effects, the power to fly, P, is given by

$$P \sim W^{3/2} b^{-1} \qquad (1)$$

Noting that area A is proportional to $b^2$, Eqn. 1 transforms to

$$P/W \sim \sqrt{\frac{W}{A}} \qquad (2)$$

Thus the power per unit weight is proportional to the square root of wing loading, and it follows that it is also is proportional to the speed for minimum power. The constant of proportionality varies inversely with glide ratio, and so the large vehicles, nature's or man's, operating at higher Reynolds numbers, will be more efficient and take less power per unit weight. However, the "square-cube law" means that as size increases, weight increases faster than area (in fact, with a square-cube law relationship between area and weight, P/W varies as $W^{1/6}$ or $b^{1/2}$. **Figure 4** shows that over a huge size range of natural and artificial flying creations (a mass range

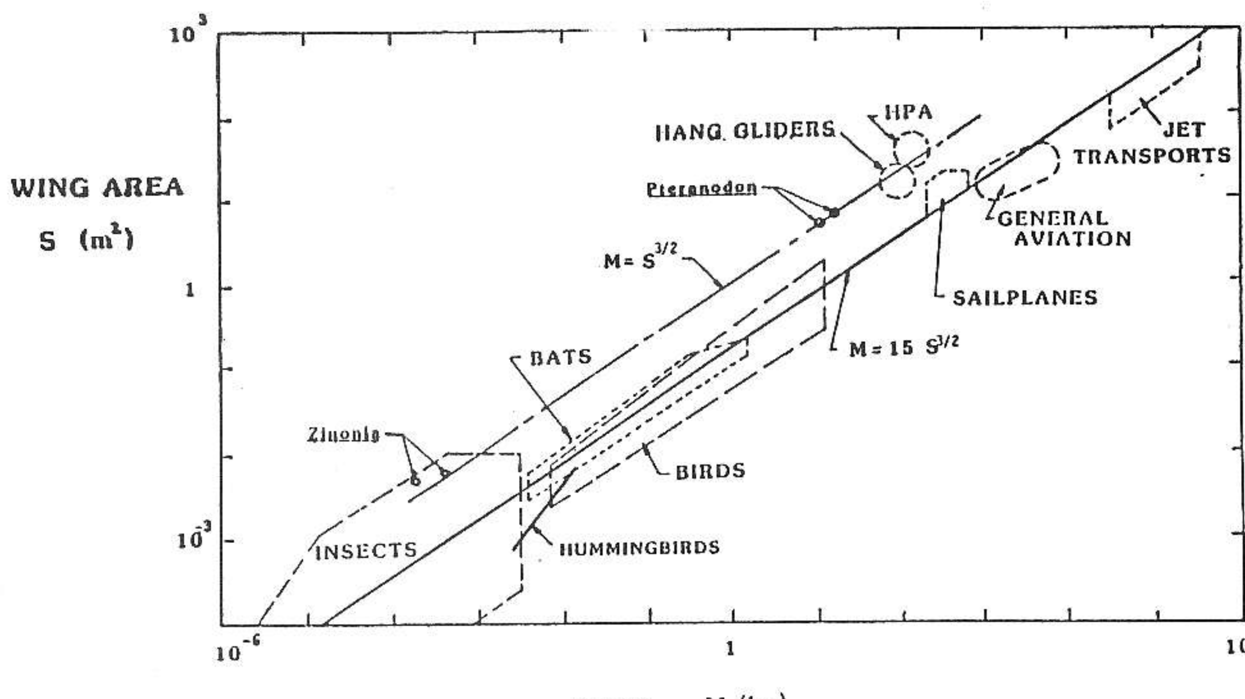



Figure 4
Variation of Wing Area with Mass (taken from McMasters, 1984)

of 10 to 1) the square-cube law relating to mass holds rather well. Significant exceptions are the Pteranodon (a large pterodactyl) and HPA (human powered aircraft). Both of these types are edging the limits of biologically-powered flight, and so feature specialized construction with low weight for their size.

What the foregoing suggests is that if large birds fly satisfactorily at wing loadings of 5 to 15 $kg/m^2$, and if man can produce comparable power-to-gross-weight ratios to birds, human flight should also be possible at comparable wing loadings. The 30 kg human-powered Gossamer Albatross with a 65 kg pilot has a lower wing loading, about 2 $kg/m^2$, than large birds. For birds, flight muscle is about one-fourth of total weight, while for a human-powered vehicle the flight muscle is more like one-tenth the gross weight. However, for a short time a human can put out two or three times the equilibrium power and so be comparable to the equilibrium of a bird, while the larger human-carrying vehicle can be more efficient due to the aerodynamic design and structure options available to the human engineer. Taking all of the above into consideration, human powered flight is not surprising. Extrapolating from the flight of soaring birds, the flight of *Quetzalcoatlus Northropi* is surprising, if the square-cube law held, because a six- or seven-fold increase in b would require a proportional increase in wing loading and a 2.5-fold increase in P/W, far more than could be made up for by slight aerodynamics improvements from Reynolds number. It is possible that the wing loading of *Quetzalcoatlus Northropi* was very little higher than that of large soaring birds of the vulture variety, and hence a biologically-reasonable P/W was maintained.

These deliberations suggest that man is not the only non-flying animal which can be permitted to maintain flight through muscle power if a suitable vehicle is provided. Animal-powered flight using a dog, mouse or even fish is conceivable, with the size of the flight vehicle being smaller than where the square-cube law inhibits flight. At the small size end of the animal-powered flight spectrum, the efficiency arising from lower wing loading (and perhaps from a higher P/W for short times arising from faster metabolism) is fighting the decreased aerodynamic efficiency due to Reynolds number effects. In summary, the dog-powered or rat-powered airplane is technically feasible, the main problems being the psychology of the animal and of animal lovers.

## NATURE VS. MAN AS ENGINEER

Attention to biological flight, whether birds, bats, pterosaurs or human-powered flight, emphasizes low power aerodynamics and structures. For manned and unmanned aircraft using fossil fuel, the stimulus of biological flight can be to raise the sights of designers. Non-refueled piloted flights with durations in weeks are achievable with existing technology.

Mother Nature has been designing birds and other flying creatures for at least 150,000,000 years. The task obviously has been well done. Every design feature meets a survival purpose, some by way of aerodynamic efficiency, others by way of biological adaptability or sexual selection. Thus a bird has elegantly handled the aerodynamic problems such as boundary layer control, stability and sensors. Basic study of bird aerodynamic features may be expected to yield valuable dividends to both research aerodynamicists and engineers.

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