

# The Biomechanics of Flight: Many Possible Solutions Looking for Problems\*

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*Aeronautics in its traditional form is usually presumed to have started as a formal engineering discipline somewhere in historical time between the mythological experiments of Daedalus and his ill-fated son Icarus, and the dreams and schemes of Leonardo da Vinci during the Italian Renaissance. As is briefly reviewed in this presentation, 'aeronautics' has a far longer (though less disciplined) history extending over a period of about 300 million years, beginning with the evolution of the ability of insects to fly. With the advent of the success of the Wright brothers, technologists quickly turned their attention from the inspirations and lessons provided by natural models of flying machines to a more practical quest for increasingly dramatic improvements in speed, range and altitude performance far beyond the limits of what muscles and flapping wings could provide. Thus a field of further productive inquiry was left to a few amateur aeronauts, eccentrics and biologists. A purpose of this paper is to remind both the biomechanics and engineering communities of what has transpired during almost a century of advance in both fields of knowledge, and what is still being discovered in the light of great progress in computational and testing technology. A more important purpose is to demonstrate some of the numerous very rich sources of inspiration and motivation such multi-disciplinary explorations offer both the engineering practitioner and educator.*

## INTRODUCTION

*A scientist discovers that which exists. An engineer creates that which never was.*

(Theodor von Karman)

*To prove that a pig cannot fly is not to devise a machine that does so.*

(Diedrich Kuchemann)

INTEREST IN and progress made during recent decades in a number of unconventional areas of aeronautics (e.g. human-powered flight, sailplanes, hang gliders, ornithopters, uninhabited air vehicles [UAVs]) remind us that all progress during the past 100 years has not been limited to mere commercial and military applications of our technology. Indeed, a closer look at the history of our aeronautical enterprise from circa 1850 to the present shows that, while not always recognized or adequately appreciated, a small band of dedicated romantics has made extraordinary progress toward realizing one of man's oldest dreams: to devise practical means for humans to truly fly like birds (or bats, or whatever). While the contributions these individuals have made to our art are too easily dismissed as being of no practical (i.e. commercial or economic) consequence, this conclusion is extraordinarily shortsighted in this author's opinion. A purpose of this present paper is to provide a complementary discussion on several elements of themes (e.g. the need for more multi-disciplinary 'systems thinking', opportunities for

design education enhancement) in the author's companion paper in this issue. As a student of, and modest participant in, the unconventional fringe of aviation over the majority of a nearly 50-year career as an aeronautical engineer and airplane design educator, the author has had the good fortune on various occasions to be given the opportunity to attempt to set the historical record on aeronautics straight(er) within a broader, multi-disciplinary context. Such an opportunity was provided by his nomination in 1992–4 (and again in 2002–4) to serve as an American Institute of Aeronautics and Astronautics (AIAA) Distinguished Lecturer, and the new DARPA Morphing Aircraft Structures Program aimed at developing concepts for aircraft capable of more-or-less radical shape change to allow them to better meet two or more divergent performance requirements (e.g. high speed dash and long endurance).

The basic premises of the lectures thus developed (generically, *The Origins and Future of Flight—A Paleoecological Engineering Perspective*) include the following observations.

The conventional view of aviation history (Fig. 1) is both incomplete and a bit backward. In large measure we owe much of our understanding of biological (both animal and botanical) flight to experience gained, and from theoretical and experimental tools developed, in the course of designing aircraft of various types, rather than the other way around. Relatively few modern aircraft either fly like, or physically resemble, biological flying devices—although arguments can be made that an increasing number probably can and should. At a minimum, we should

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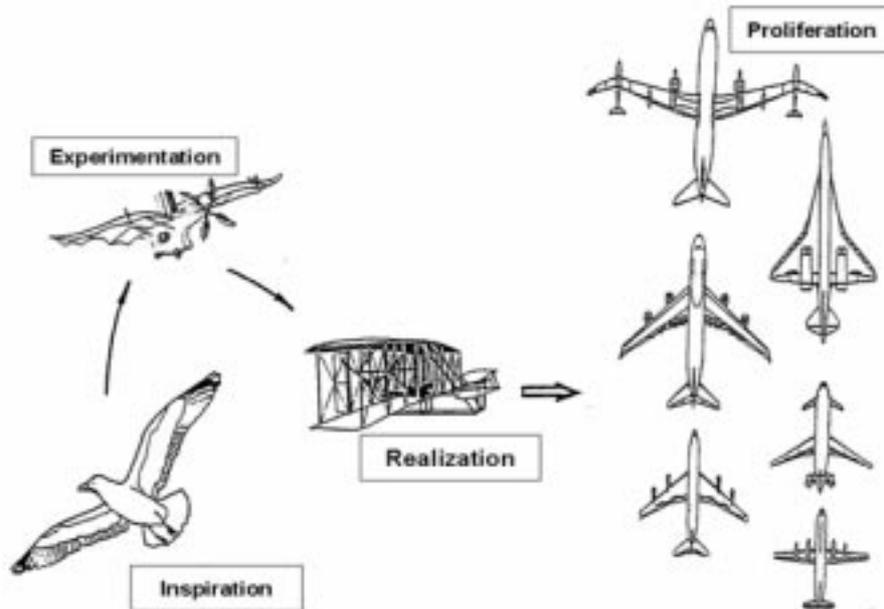


Fig. 1. The traditional view of the history of aviation.

understand aviation history in the broader terms shown in Fig. 2.

Engineers, working closely with others from a range of scientific disciplines (e.g. zoology, botany, paleontology, neuro-physiology, geology, and particularly ecology), have much to contribute to

increasing our understanding of flight in nature and engineering in general. The reverse of this proposition has yet to be adequately exploited—and should be in the future, especially as environmental concerns increasingly come to influence future technical developments.

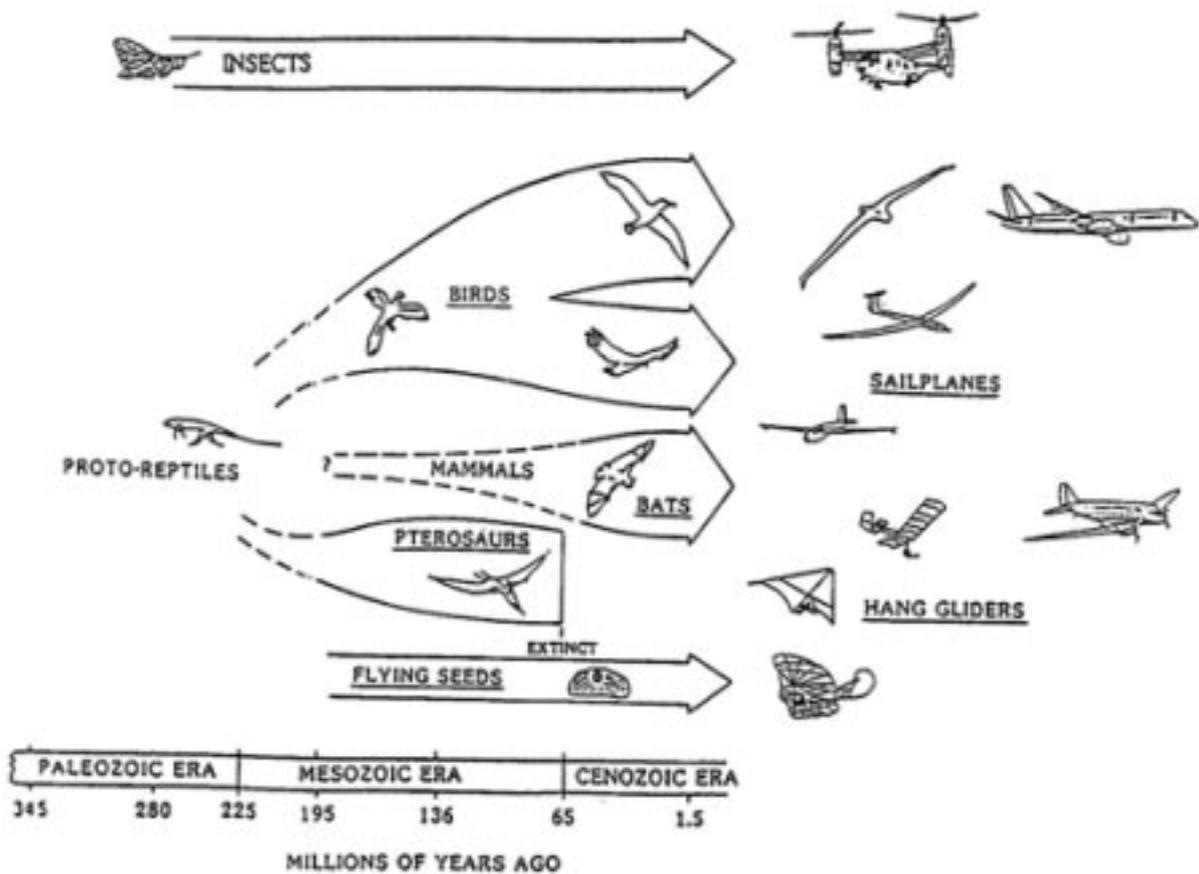


Fig. 2. A more complete view of the history of aeronautics.

Rather than being separate, disconnected topics, technological and biological flight represent two portions of a continuous, very broad and fascinating spectrum. A huge range of diverse devices and configurations are all tied together by the underlying requirements that each must obey the same fundamental laws of physics, chemistry—and economics.

To understand the apparent differences in devices as dissimilar as dragonflies, seagulls and jet transports, one must understand not only the basic physics of flight but also the context within which each operates. This context is spatial, temporal (covering several *hundred* million years of evolution) and economic. Thus, as in any form of traditional airplane design problem, an 'ecological' (system) perspective must be adopted. In short, the aerodynamic aspects of the design problem, for example, do not exist in pristine isolation and any attempt to discuss a history of a single discipline such as applied aerodynamics or structural mechanics must correctly include an encompassing view of the overall system to which our art contributes and by which its ideal applications are constrained.

Much of the materials for these lectures (which have continued to grow and evolve) came from a semi-avocational interest, research and subsequent writings on topics relating to the overlap between the spectrums of biological and technological flying devices, beginning with small (microscopic) insects and pollen grains through aircraft substantially larger than the current Boeing 747. Thus

attention has been drawn (cf. Fig. 2) to the equivalence between large soaring birds (condors and extinct teratorns) and sailplanes; pterosaurs, hang gliders and ultra-light sailplanes; human-powered aircraft; and at the other end of the biomechanical spectrum to the fundamental importance of aerodynamics in the sex life of grasses and the dispersal of aerosols.

### POSSIBLE APPLICATIONS OF BIOMECHANICS TO TECHNOLOGY

The benefits of these inquiries to the author's professional work, as an educator, aerodynamicist and airplane designer, have been many. Perhaps the most important has been the deep appreciation gained for the importance of *size* (e.g. Fig. 3) and hence the importance of both fluid dynamic and structural scale effects on airplane (and animal/plant) design problems. Even simple physics-based analyses within the reach mathematically of a high-school student (e.g. the square-cube law, simple beam theory, the conservation laws of momentum and energy) can give insightful results. Other topics of major practical importance that are well demonstrated in natural flying devices are advanced manufacturing techniques, the various uses of vortices for flow control, the effects and benefits of aeroelasticity and variable geometry, and (particularly in the case of insects) the problems and benefits of controlled large-scale *unsteady* separated aerodynamic flows.

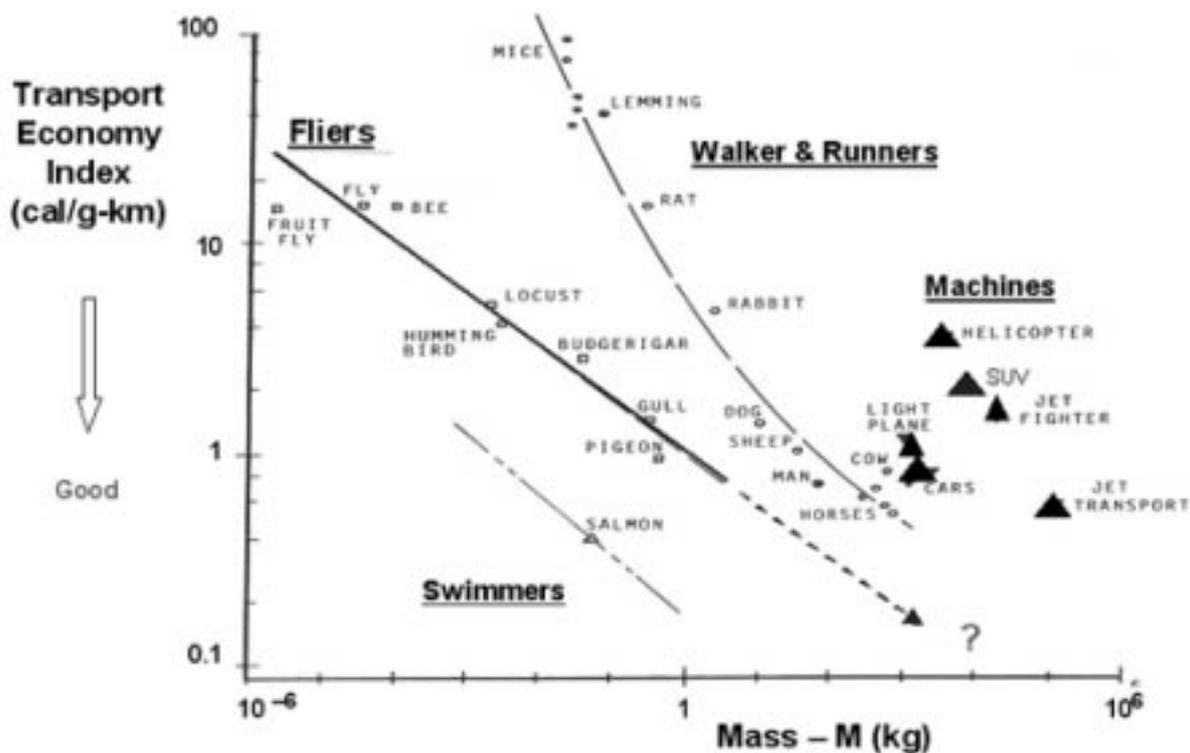


Fig. 3. The virtues in specific energy consumption from flying and size (the transportation economy index = energy consumed per unit weight per unit distance traveled).

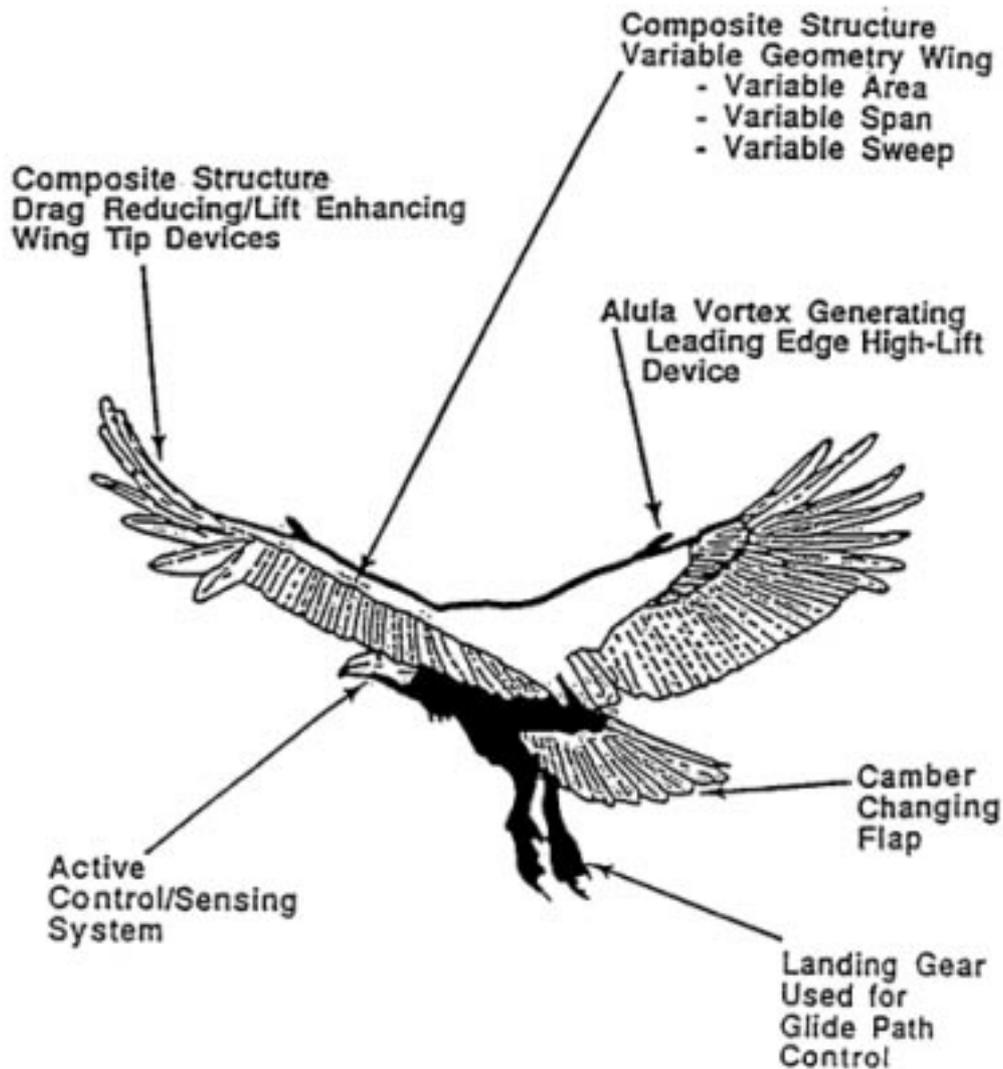


Fig. 4. A condor (*Gymnogyps californianus*) in a low-speed glide, illustrating that birds incorporate important aeronautical technology, including: mission-adaptive wings, active controls and control, configured vehicles, composite structures, damage-tolerant structures, fully-integrated systems design and advanced manufacturing.

In this last connection, the author has not shared the enthusiasm of some recent investigators for ornithopters (flapping wing aircraft), based largely on his strong prejudice against reciprocating machinery. It should be noted here that, with what was until recently thought to be the singular exception of certain bacteria (e.g. *E. coli*), nature has not had the benefit of the wheel as a means of aiding locomotion. Thus, birds and all other active natural fliers (as contrasted with passive gliders or parachuters) have had to rely on flapping their wings to provide propulsion. This has been thought to be 'primitive' and limiting—at least with regard to the flight speeds thus achievable by such means. And so the issue has stood until recent interest in micro-UAVs (e.g. robotic 'insects') has forced a re-evaluation of the question of whether, *at the scale (size) conditions involved*, it is in fact wiser to combine the lift and thrust generating mechanisms than to separate them. The answer may well be that the combination of functions is the best answer in this singular

design problem, at least in part for reasons reviewed in one of the author's earlier publications [1]. Fortunately, there is now an increasing body of very good literature available [2, 3] that allows more detailed quantitative assessments of the necessary trades to be made.

The study of the biomechanics of insects is but one area among many wherein we can now see in retrospect that nature had (and still has) much to teach us regarding the possible future development of our art and our technology. Even more fruitful is the study of the three lines of development of the ability to fly among the vertebrate animals (birds, bats and now extinct pterosaurs). Modern birds in particular already fully and elegantly embody a number of items that have been the subject of much research and development in aviation in recent decades. As shown in Fig. 4 for the case of the California condor, these items include variable geometry (mission adaptive) wings, an advanced high-lift system, an active ('fly-by-wire') control system, a self-repairing/self-reproducing composite

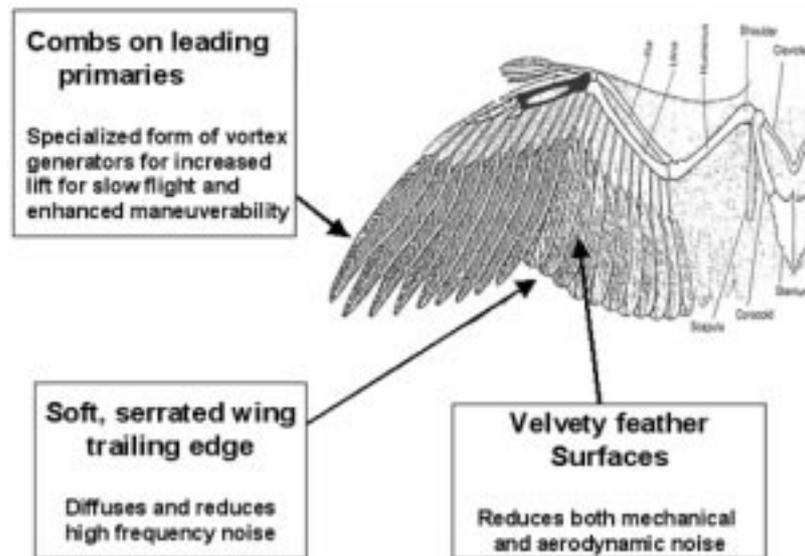


Fig. 5. Quiet, maneuverable flight adaptations of owl wings.

structure, and fully integrated system architecture. All this offers a vast abundance of case study examples of good design (in an integrated system sense), possible subjects for student project and thesis topics, and, above all, a stimulant to students' imagination and creativity.

A singularly good example of nature's complex adaptations is embodied in the design of many species of owl, and will suffice to demonstrate the possibilities such inquiry offers. Many further examples may be found in the literature cited in the bibliography section of this paper.

### THE QUIET, MANEUVERABLE FLIGHT OF OWLS—A CASE STUDY

Owls are highly evolved and specially adapted primarily as nocturnal predators, often flying in confined spaces such that they need to fly slowly and with a high degree of maneuverability. They are also splendid examples of natural 'stealth' technology in that their approach is not detectable by prey while using highly developed bi-aural direction finding and night vision.

The owl's wing adaptations to do these two things, as shown in Fig. 5, are often confused with each other, and they turn out to be synergistic.

How this is done may be understood by working from some basic principles:

- Any object (e.g. a wing) moving in a fluid (e.g. air, water) generates a system of forces (e.g. lift, resistance or drag) and noise (fluctuating pressures or sound waves of various dissonant frequencies and intensities).
- Whether an object is moving in a stationary fluid or the fluid is flowing over a stationary object does not matter; what is important is the

speed of the flow *relative* to the speed of the object. If the relative speed is zero there is no force or noise generated.

- The noise generated depends theoretically on:
  - the fifth power of the relative speed between the flow and the object;
  - the inverse square of the distance between the object and a receiver; and
  - the details of the shape and size of the object.
- The forces generated depend on:
  - the size of the object (primarily its surface area exposed to the flow);
  - the square of the relative speed (for a gliding bird not flapping its wings, the square of the flight speed); and
  - a force (lift and drag) coefficient dependent on the shape and attitude (e.g. 'angle of attack') of the reference axis of the object relative to the flight direction.

From these basic principles, the following specifics can be derived:

- The aerodynamic forces on a wing (needed to fly—i.e. create *lift* to balance the animal's weight—or to maneuver) vary according to the area of the wing and the *square* of the flight speed. Everything else being equal, *doubling* the flight speed increases the forces on the wing by a factor of *four*. *This works both ways*. Slowing down rapidly reduces the forces produced unless other special measures are taken to increase them (e.g. fitting a wing with auxiliary high lift devices like wing flaps or leading edge slats). Many birds, including owls, use their tails as 'flaps' to enhance lift available from their wings. Creating extra lift also creates extra drag, however.
- Everything else being equal, the noise generated by a bird flying through the air varies theoretically as the *fifth* power of the flight speed and the

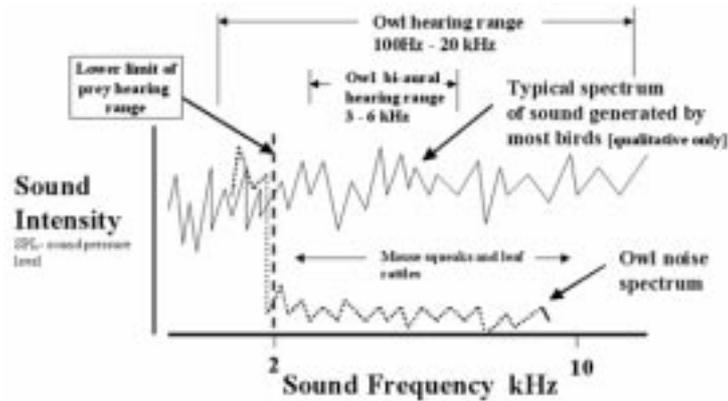


Fig. 6. Notional comparison of the noise spectrum of owls relative to their prey and other types of birds.

inverse square of the distance between the bird and its prey. Thus, doubling flight speed increases noise intensity by a factor of 32. Doubling the distance between the owl and its prey *reduces* the noise heard by a factor of four.

Therefore, for an owl to fly slowly (and thus with low noise) and with the necessary ability to maneuver, a wing of relatively large area for its body weight (i.e. a low ‘wing loading’) is needed. This is combined with special micro comb-like structures on the leading edges of the leading primaries (Fig. 5) that generate vortices that increase lift on the outboard portions of the wing.

To reduce noise audible to their prey (and not interfere with their own hearing and direction finding), the owl has feathers with a velvety surface texture that reduce mechanical rubbing and rattle and which ‘kill’ higher frequency air flow noise. Further, a soft and serrated wing trailing edge diffuses and damps higher frequency components of airflow noise.

Thus we find that owls do not really fly ‘noiselessly’, their special adaptations merely manage the noise they generate by a clever combination of suppression and frequency shifting within the limited range of the hearing ability of their prey until it is too late to avoid an attack, as shown in Fig. 6. Owls are thus very cleverly adapted for

what they do (and where and when they do it), and several features of owl feathers are unique among birds (leading edge combs, velvety feathers, soft wing trailing edges). Not all owls have all these adaptations (e.g. fishing owls lack leading edge combs). Experiments in which the leading edge wing combs and trailing edge fringe were clipped from the wing showed a large deterioration in an owl’s ability to fly—and noise generated more like that of other birds. Selective reading of the bibliographical material listed in the sense shown in Fig. 7 should give an adequate flavor of a very rich and rewarding field of such further inquiry.

**SOME CONCLUSIONS OF A CONTINUING WORK IN PROGRESS**

We have made amazing progress during the first century of powered human flight in terms of *farther, faster, higher*—and we have far exceeded all of nature’s fliers in these regards. On the other hand, we have yet to develop a self-repairing airplane that can lay eggs and reproduce itself. In the case of the DARPA project noted earlier, perhaps there is more potential in the development of ‘cloning’ rather than ‘morphing’ structural technology. Regardless of the potential applicability of



Fig. 7. The knowledge management domain: new worlds to explore, originally developed by L. Matsch (allied signal aerospace) and J. McMasters under the auspices of the Boeing-initiated industry-university-government roundtable for enhancing engineering education [IUGREEE] in 1997–98.

natural models to the solution of human-scale technical problems, the study of the paleoecology (the **whole** system) of natural flight makes a grand hobby, encompassing life, the universe and just about everything else. At a minimum, it also provides some of the inspirational tent poles that keep our imaginations from collapsing around us.

When the author first discovered the possibilities

these sources offered, it was considered largely frivolous by both his peers and mentors in the traditional engineering community. Fortunately, thanks to the major contributions made since then by engineering scientists and mathematicians like Lighthill [4, 5] and the legion of subsequent investigators they have inspired, this is no longer the case and much of real value has since been learned.

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