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AN ANALYTIC SURVEY OF LOW-SPEED FLYING DEVICES - NATURAL AND MAN-MADE

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INTRODUCTION

Aeronautical design can be viewed from several vantages: detail design where one is concerned with the precise characteristics of a single component in a particular aircraft, preliminary design in which the main concern is for the overall characteristics of a particular type of aircraft, and finally the design survey in which the characteristics of several classes of flying device are compared to each other. It is useful to periodically assume this latter point of view in order to put the current state-of-the-art in perspective, to include new information which may have become available and to make a general assessment of the present and potential performance of a new class of vehicles not previously considered. Two notable examples of this sort of exercise are those by von Karman (1) and Cleveland (2). Many of these studies take a somewhat limited view covering a small range of vehicle sizes, weights and/or performance.

The present paper is a brief summary of a larger study (3) whose goal is to present a modern overview of the geometric and energetic relations of a very wide spectrum of flying devices covering the range from small insects to large jet transport aircraft. The particular focus of this study is on those machines which fall in the size, weight and speed transition region between natural fliers (birds, bats) and conventional powered light aircraft. It is hoped that the potential for human flight in this poorly studied region can thus be illuminated and placed in perspective.

A secondary goal of the general study (3) is to assemble data on the topic area from a wide variety of sources, many of which are outside the usual realm of familiarity to the practicing engineer. As an example, a very large body of published work on the energetics and aerodynamic performance of birds and insects is accumulating in the biological literature and to the authors' knowledge has not been widely publicized in aeronautical journals. Nature continues to provide a wealth of information and inspiration for the engineers and designers of man-made devices and in aeronautics this is particularly true in the rapidly expanding fields of ultra-light (4) and motorless flight. For this reason, an up-to-date survey of the sort presented here may be timely.

The basic inspirations and motivation for undertaking this survey were the paper by Shenstone (5) and the book by Hertel (6). Further study lead to discovery of the publications by Gabrielli and von Karman (7), Greenwalt (8), Hartmann (9), Schmidt-Nielsen (10), Pringle (11), Raspet (12), and most importantly, Pennycuick (13-24) and Tucker (25-30). Data from these sources form the basis of the natural flight systems portion of this study.

The primary concern of this study are those devices one can classify as "low-speed". In practice this will be taken to mean those devices which normally operate at speeds below Mach 0.2 and at Reynolds numbers (based on average wing chord) below 10^7. An important omission in this survey has been the whole range of model airplanes. In addition the entire topic of ornithopics (flapping wing flight) is treated only cursorily. A sample of the quantitative data used in this survey is presented in Table 1. The general arrangements of representative examples of each type of device are shown in Figure 1.

Low Speed Flying Devices

Human dreams of flight have always been encouraged by the natural models placed before them. It is instructive in judging the success of man-made flying machines to compare them against those developed by nature. Nature's fliers have the advantage of having undergone developmental time scales of enormous duration, the humbling magnitudes of which are shown in Figure 2. Further, one should keep in mind Welty's (31) observation: "Birds (etc.) simply dare not deviate widely from sound aerodynamic design. Nature liquidates deviationists much more consistently and drastically than does any totalitarian dictator".

Five categories of natural fliers are of particular interest in this survey: insects, soaring birds, bats, Pterosauria and animophilous (wind dispersed) seeds. Several other types could be cited and the interested reader is referred to Hertel's book (6).

Insects: Understanding insect flight is important because it has major human economic and hygienic implications. Detailed flight performance measurements on only a few types of insects have been made, the most impressive investigation being that on the desert locust (Schistocerca gregaria) by Weis-Fogh and Jensen (11,32). Vogel (33) has done similar work with fruit flies (Drosophila).

As the dimensional data in (8) indicates, insects come in a bewildering array of sizes and shapes and the limited performance data presently available does not permit general statements to be made about how all insects fly. A few observations can be made, however. Weis-Fogh and Jensen have shown that the motion of the locust wing through each cycle is quite complex and analyses based on assumptions of simple harmonic motion are not adequate. Weis-Fogh further noted that insect muscles are remarkably efficient although the proper value (whether 14% or 20%) requires considerable qualification. An interesting aspect of insect flight is its dependence on atmospheric motion. The book by Chauvin (35) on this topic is most illuminating. Insects basically operate in close proximity to the ground and are usually found at high altitudes (AGL) only when blown there by the wind. Hertel (6) presents some good information on the structure and form of insect wings.

Birds: Bird flight has been the subject of serious scientific inquiry for several centuries. Unfortunately, there remains as much mythology as hard data on many aspects of bird flight performance. The whole topic defied brief exposition, however, and the main discussion here must be limited to those birds whose flight behavior is of most immediate interest in human flight (i.e. soaring birds). The most recent major attempt to formulate a detailed quantitative theory of the flapping flight of bird is that by Cone (36). The simpler analysis by Tucker (28) appears adequate for making preliminary estimates, however.

Soaring birds have been watched with awe since the emergence of man and a good discussion of early investigations of their performance has been presented by Cone (37, 38). Of great technical interest is the major differences in wing planform between large land soaring birds and their maritime dwelling counterparts. Figure 3 shows the nature of this difference in comparing the shapes of two of the largest existing examples of these types. The aerodynamic design of the albatross can be easily grasped in the light of modern aerodynamic theory. Large vultures, hawks and eagles are known as very efficient soaring birds and yet they uniformly have broad wings with aspect ratios

TABLE 1. VEHICLE CHARACTERISTICS

Type	Wing Span (m)	Wing Area (m^2)	Aspect Ratio	Load Mass (kg)	Wing Load. (N/m^2)	Cruise Speed (m/s)	$\frac{P_n}{M}$ (W/kg)	P_e/WV $\frac{(W\text{-}S)}{(N\text{-}m)}$	Ref.
Insects:									
1. House fly (Musca)	0.013	2x 10^{-5}		1.2 x 10^{-5}	5.9	2.0	166		26,34
2. Butterfly (Papillio)	0.082	3.6x 10^{-3}	1.87	$3\text{x}10^{-4}$	0.82	3.5			8
3. Locust (Schistocerca)	0.10	2 x 10^{-3}	5.0	2 x 10^{-3}	9.8	4.15	87		11,32
4. Blue Dragonfly (Aeschna)	0.10	1.85 x10^{-3}		1.5 x 10^{-4}	0.8	10			6
Birds:									
5. Pigeon (Columba)	0.65- 0.25	0.063- 0.038	6.7- 1.6	0.4	62- 102	12.4	67.5	0.185^+	14
6. Fulmar petrel. (Fulmaris)	1.09	0.102	11.7	0.725	69.5	12.2		0.120^+	13
7. Black vulture (Coragyps)	1.32 1.44	0.323 0.364	5.4 5.7	1.79 2.30	54 62	12.5 15		0.088 0.045	39 12
8. White-backed vult. (Gyps)	2.2	0.69	7.0	5.4	76.5	13	$(3.64)^+$	0.066	15
9. Rüppel's Griff. vult. (Gyps)	2.5	0.83	7.55	7.5	88.5	14.5		0.0625	16
10. Wand. albatross (Diomedae)	3.5 3.45	0.60 0.725	20.4 16.5	9.2 9.8	150 132	20 16		0.050 0.052	43 41
Bats:									
11. Dog-faced bat (Rousettus)	0.461 0.554	0.04 0.057	5.32 5.42	0.119	20.6- 29.2	8		0,156	17
Pterosaur:									
12. Pteranodon	7 7.6	4.2 4.6	11.5 12.5	16 11.3	37- 24	9 8		0.050 0.087	48 3,47
Anemophilous Seed:									
13. Zinonia	0.15 0.115	6.2-3 5-3	3.63 2.65	3-4 1.75-4	0.475 0.343				50 6
Hang Gliders:									
14. Typ. Std. Rogallo	6.58	18.4	2.36	81.5	43.5	10		0.25	4
15. Eipperformance "Quicksilver B"	9.15	10.75	2.65	81- 118	74- 108	9.8		0.143	4
16. Kiceniuk "Icarus V"	9.75	14.9	6.4	100	65.8	10		0.1	4
17. Volmer Jensen VJ-24	11.1	15.15	8.15	141	91	9		0.1	4

TABLE 1. VEHICLE CHARACTERISTICS (Cont'd)

Type	Wing Span (m)	Wing Area (m^2)	Aspect Ratio	Load Mass (kg)	Wing Load. (N/m^2)	Cruise Speed (m/s)	$\frac{P_n}{M}$ (W/kg)	P_e/WV $\frac{(W-S)}{(N-m)}$	Ref
Man-Powered Aircraft:									
18. Hatfield "Puffin II"	28.4	36.3	22.2	132	35.7	8^{**} (8.7)	14.3^{**} (17.5)	0.028^{**} (0.032)	52
19. Herts. "Toucan"	37.5	55.8	25.2	240	42.2	8.25^{**} (9.2)	13.1^{**} (17.4)	0.025^{**} (0.030)	52
20. Weybridge "Dumbo"	36.7	44.6	30.2	127	27.9	7.45^{**} (8.0)	11.0^{**} (13.8)	0.023^{**} (0.027)	52
Motor Glider:									
21. Scheibe SF-27M	15	12.1	18.6	370	300	34.2		0.032	Zacher 55
Sailplanes:									
22. Schweizer 1-26	12.2	14.9	10	270	178	21.6	39.5	0.0465	56
23. Schempp-Hirth "Std. Cirrus"	15	10.0	22.5	333	326	26.2	29.6	0.0264	56
24. Schleicher AS-W-12	18.3	13.0	25.8	412	311	24.6	22.6	0.0231	56
25. VVG	18.6	10.25	33.8		477	30.5			
Design Study	19.0	16.3	22.3	500	300		27.6	0.0230	3
General Aviation:									
26. Piper PA-18"Super Cub"	10.76	16.58	7.0	794	479	32	157	0.09	
27. Beech "Bonanza"	10.2	16.8	6.2	1417	830	48	192	0.075	
28. Cessna 310F	10.9	16.3	7.3	2190	1320	56	209	0.071	
Jet Transports:									
29. McD.-Douglas DC-9-20	28.4	93.[illegible]	8.7	4×10^4	4200	190	580	0.055	
30. Boeing B-707-320	44.4	274	7.2	1.22×10^5	4400	210	523	0.059	
31. Boeing B-747	59.6	511	6.95	2.8×10^5	5400	240	420	0.059	

** Flight in ground effect at 3 m height

+ Power-off glide

++ Half fuel weight

Note: All numbered data points on Figures 6 and 10-13 correspond to the entries in Table 1.

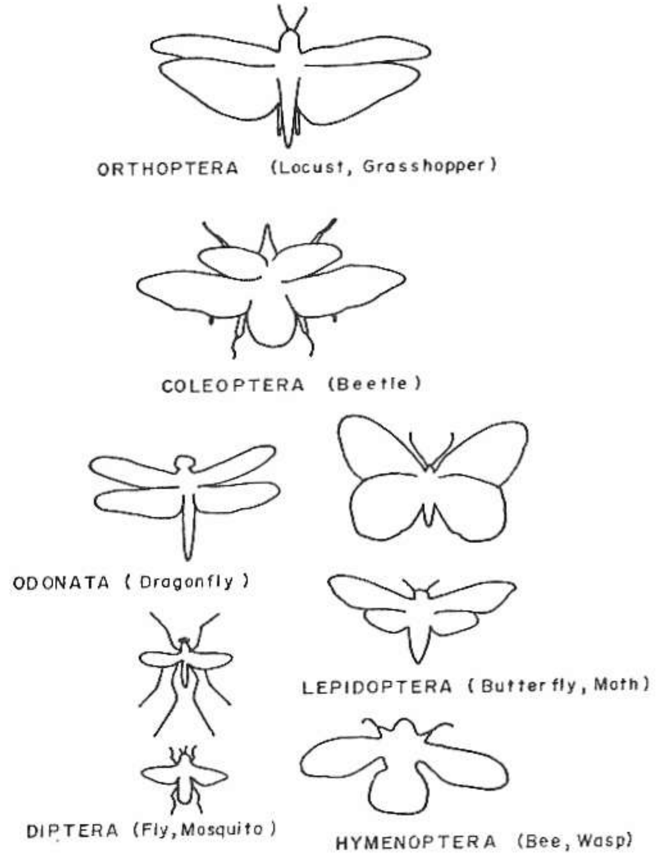


FIGURE 1(a). Comparison of Typical Insect Wing Planforms

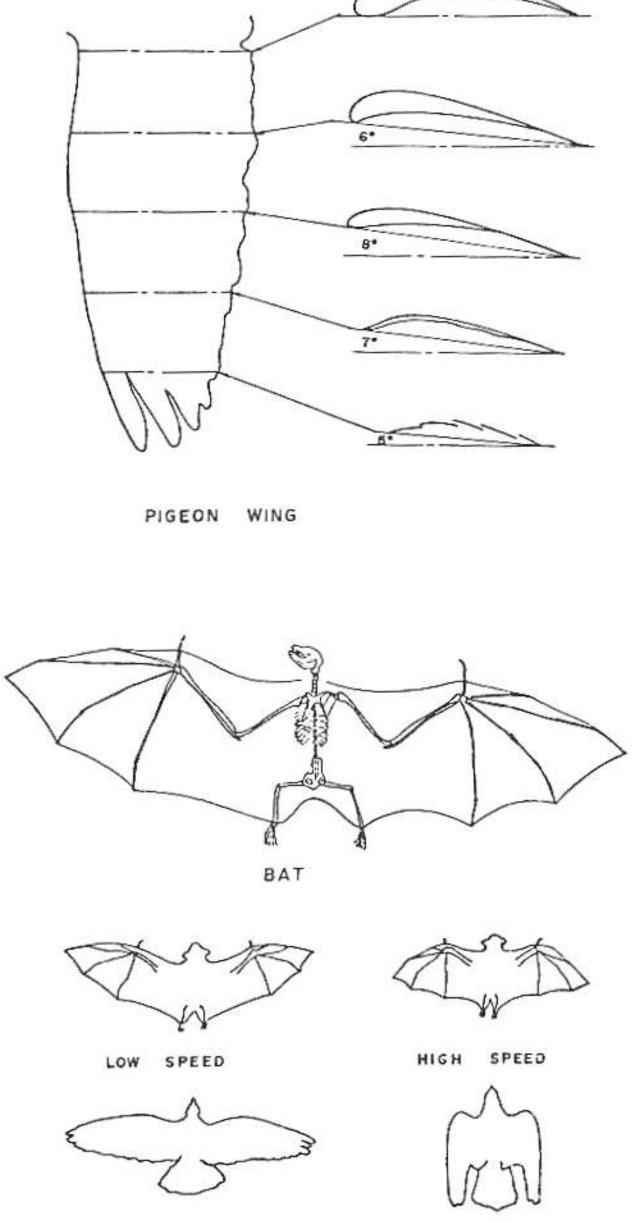


FIGURE 1(b). Typical Bird and Bat Wing Planforms

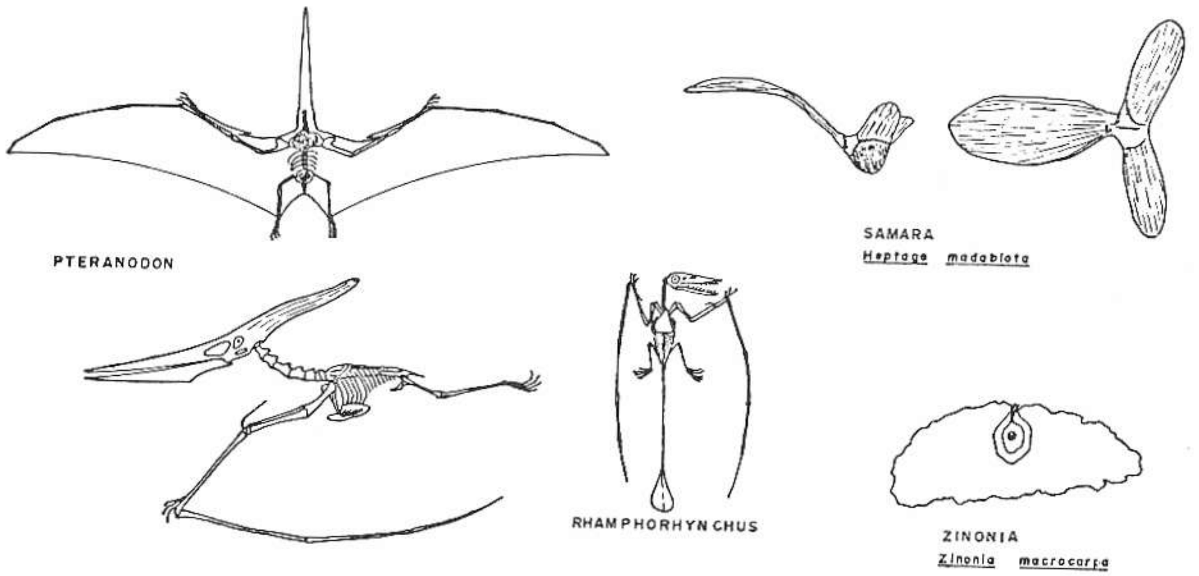


FIGURE 1(c). Pterosaur and Animophilous Seed Configurations

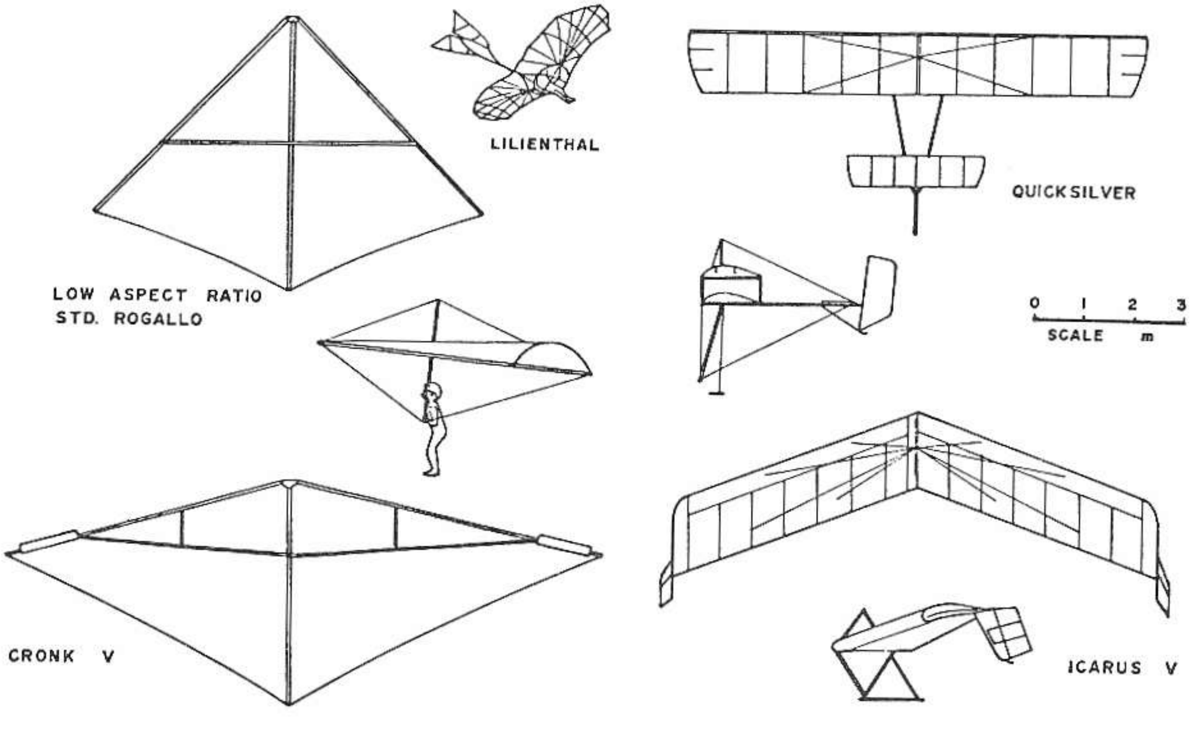


FIGURE 1(d). Hang Glider Planforms

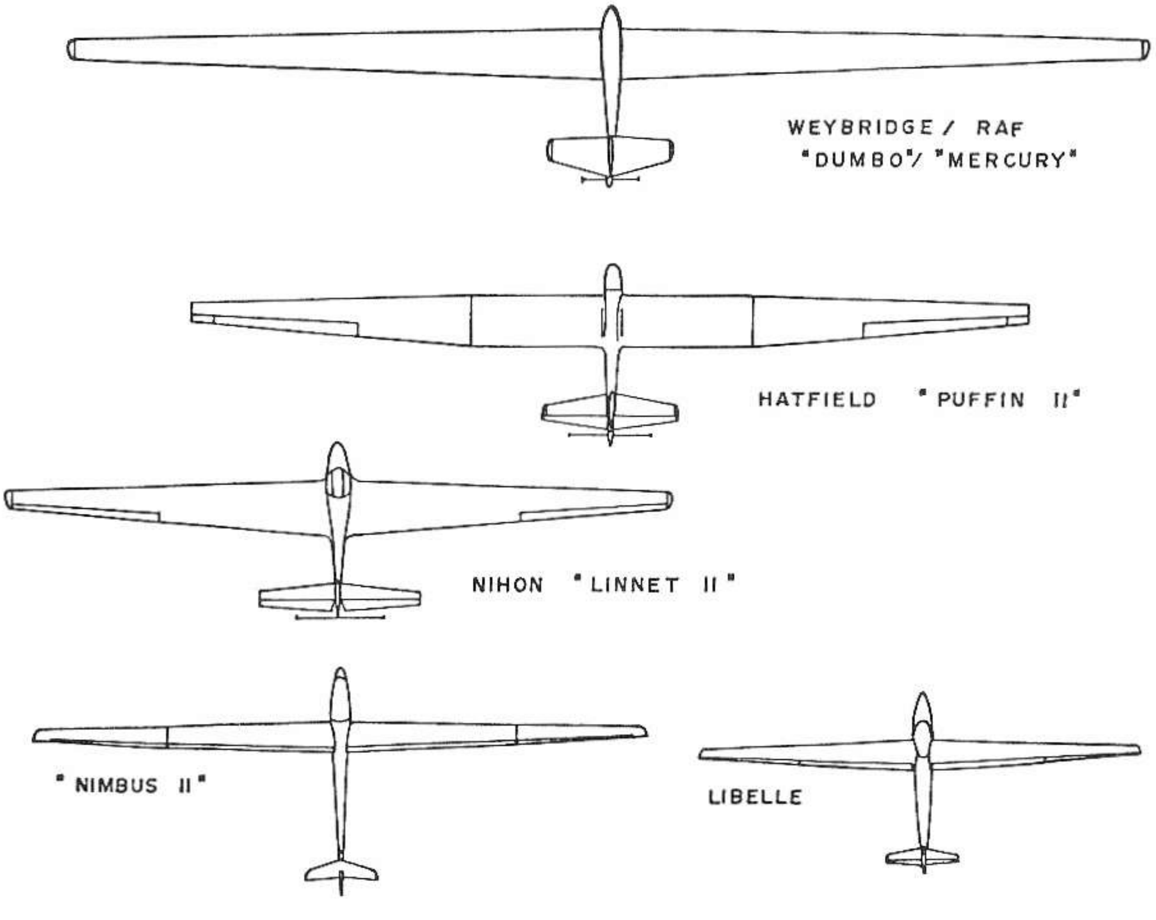


FIGURE 1(e). Man Powered Aircraft and Sailplane Size and Planform Comparison

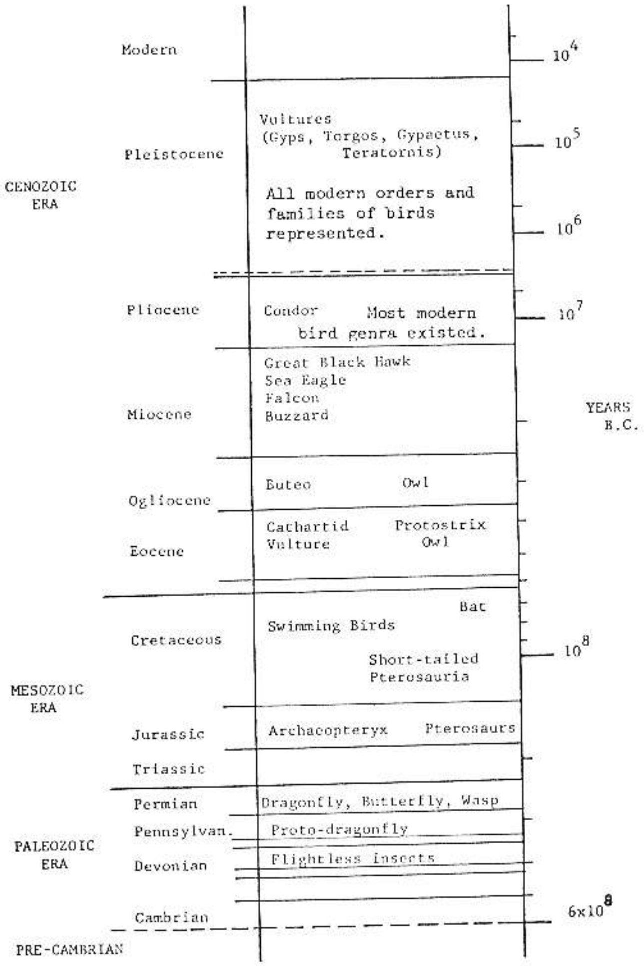
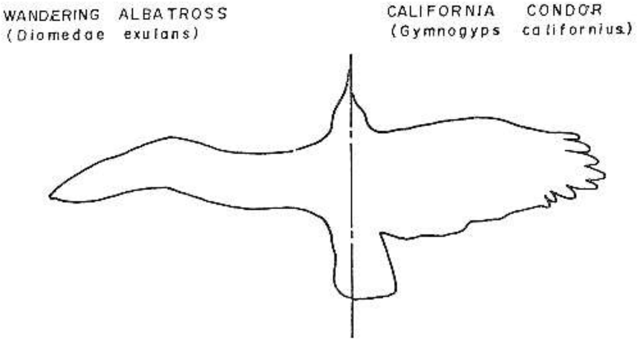


FIGURE 2. Evolutionary Time Scale



	ALBATROSS	CONDOR
WING SPAN (m)	3.5	3.0
WING AREA (m^2)	0.72	1.5
ASPECT RATIO	17	6
MASS (kg)	9.8	10
WING LOADING (N/m^2)	133	65

FIGURE 3. Planform Comparison of Large Land and Sea Soaring Birds

seldom exceeding 7 or 8 with very large pinion feathers which are held in a splayed arrangement while soaring at low speed. The actual function of this pinion arrangement shown in Figure 4, remains the subject of some debate stimulated by the work of Raspet (12) in the 1950's. Raspet can be credited with attempting to make the first detailed measurements of the performance of land soaring birds by chasing black vultures (Coragyps atratus) in a sailplane of known performance. Raspet credited the vulture with a maximum glide ratio of 23 at a speed of 15 m/s. He attributed this apparently spectacular performance to a number of possible factors including a significant increase in effective aspect ratio due to the splayed pinion feathers and the possibility that the feathers in general provided drag reducing boundary layer control.

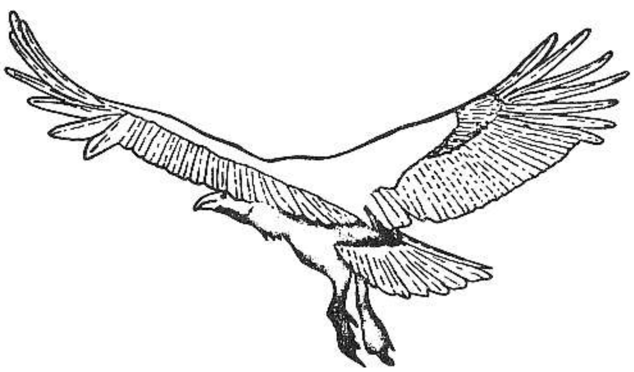


FIGURE 4. Condor (Gymnogyps californius) in a Low Speed Glide with Glide Path Control Devices (feet) Extended

Later wind tunnel tests of live birds (including a black vulture) by Tucker and Parrot (30,39) and measurements made by Pennycuick (15, 16, 23, 24) using Raspet's technique with an AS-K-14 motor glider show that Raspet's L/D value of 23 was far too optimistic, a more realistic value being about 12, although Parrot's data particularly, can also be criticized. Knowledgeable authorities (40) continue to publish Raspet's original data. The questions raised by this controversy are fascinating and should yield to careful theoretical analysis. It may then be desirable to apply mechanical equivalents of the vultures pinions to a variety of ultra-light human carrying aircraft whose operational requirements are similar to those of the bird.

Analyses and measurements of sea soaring birds appear in (12), (13), (27), (41), (42) and (43). Of general interest here is the common use of radical variable geometry techniques by birds. The wing skeletal and feather arrangement allows the bird to greatly alter both its wing span and area to match a given flight condition. The example of the fulmar shown in Figure 5, demonstrates the extent of this capability. This feature also makes accurate geometric size descriptions of birds difficult.

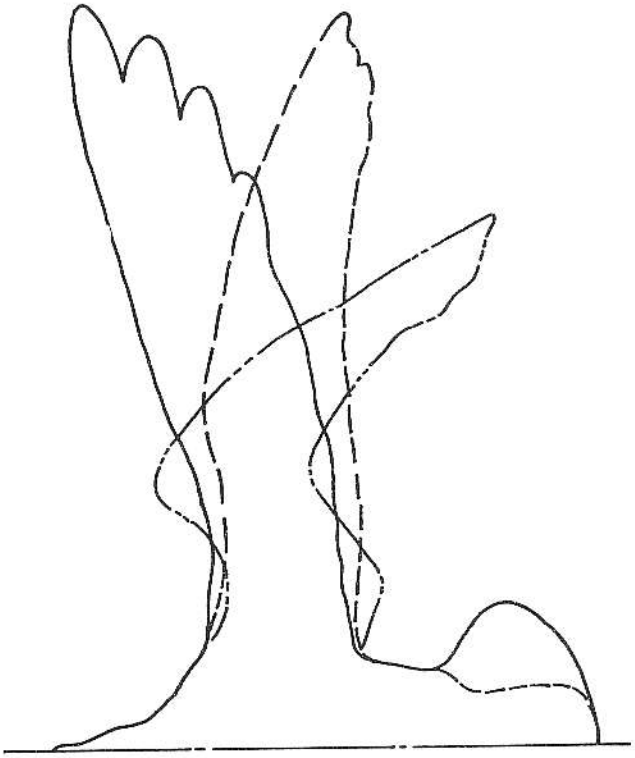


FIGURE 5. Variable Geometry Capability of the Fulmar Petrel (Fulmaris)

A number of the internal adaptations to maximize a bird's flying ability are of interest. Welty (31, 44) has outlined many of these and perhaps most interesting to the engineer is the detailed structure of bird skeletons. This aspect is also discussed by Hertel (6). Pennycuick (18, 19) has extensively examined the strength of pigeon (Columba) wings and flight muscles and has found that analogous to the example of several fiberglass sailplanes, the structure has an ultimate load factor substantially in excess of extreme flight loads which could realistically be imposed upon it. Whether this is the case with other birds remains an open question. A final, potentially fascinating unanswered question are the possible functions of the feathers. As an example, Galvao (45) has suggested that feathers may act as, among other things, acoustic dampers which delay transition in the wing boundary layer.

Bats: Bats represent an important class of natural flier, but for a variety of reasons their aerodynamics have been relatively poorly studied to date. The most important references on this topic at present are (17) and (46). Aside from the fact that bats are mammals, they exhibit many of the internal functional adaptations (hollow bones, highly efficient respiratory system, etc.) common in birds.

The most striking technical difference between birds and bats is that of the form and structure of their wings. The stretched membrane surface of the bat wing supported by the enormously elongated "finger bones" contrasts starkly with the finely contoured and feathered surface of bird wings. Pennycuick (17), however, has shown that the aerodynamic efficiency of the bat and the pigeon in gliding flight are generally quite similar although there are important detailed differences. These relate to differing operational requirements and the basic mechanical structures of the wings. The structure of the bat does not permit it to change its wing span in flight to the extent a bird can without suffering collapse of the entire lifting surface. On the other hand, the bat, by virtue of its articulating "fingers" can radically alter the camber and aerodynamic twist of its wing. A bird has relatively limited capabilities in this respect. The membranous surface of the bat's wing is of interest also, possessing a quality like "elastic sear sucker" which allows the skin to remain taut in all normal flight configurations.

Pterosaurs: The prehistoric flying reptiles of the Order Ptersauria have caused controversy ever since the discovery of their first fossil remains in the late 18th century. Ranging in size from that of a small sparrow to the gigantic Pteranodon (47) with wings spanning up to 8 m, the entire group has often been dismissed as aerodynamically crude and primative. This assessment ignores the fact that the order was sufficiently viable to have existed for 100 million years. One of the fundamental questions about the pterosaurs has been: How did they operate and in what environment? Recent analysis by Whitfield and Bramwell (48) and operational experience with Rogallo hang wing gliders (49) cast considerable light on this subject.

Animophilous Seeds: The final category of natural flier considered here is the range of "flying seeds". A good discussion on these is presented by Hertel (6). Of particular interest, both technically and historically, is the seed of the Javan palm, Zinonia macrocarpa (6, 49, 50).

Five types of man-made low speed flying machines are considered in this survey: hang gliders, man-powered aircraft, sailplanes, motor gliders, and General Aviation (light, powered) aircraft. In addition, some typical data on jet transport aircraft. In addition, some typical data on jet transport aircraft are included to tie down the upper end of the size/weight spectrum, despite the fact that these aircraft are in no way "low speed" types.

Hang Gliders: Hang gliders have the distinction of being the first type of aircraft to introduce humans to aerodynamically supported flight. While an apparent anachronism now, the sport of hang gliding has very recently become a rapidly growing branch of sport aviation. Technical aspects and numerous references are cited in (4).

Man-Powered Aircraft: A variety of human powered flight schemes have been proposed (51, 52), but almost all hardware development within the last fifteen years has been guided by the requirements of the British Kremer Competition. The "successful" MPA's built in this period have been uniformly huge, extremely light weight, very fragile machines, designed to exploit beneficial reductions in induced drag while flying in ground effect.

Sailplanes: The development of the modern, high performance fiberglass sailplane is perhaps the major human triumph in low-speed flight. No single recent publication adequately describes the full history of soaring and sailplane development. The best sources of recent information on the subject are SOARING magazine (the journal of the Soaring Society of America), its British counterpart SAILPLANE AND GLIDING, the Swiss journal AERO-REVUE and (53, 54, 55). Of particular value in appreciating the current state of sailplane development are the results of the extensive flight tests conducted by Bikle (56), and von Laurson and Zacher (57).

Motor Gliders: Motor gliders are sailplanes or gliders fitted with small engines intended mainly to provide them with a self-launching and retrieval capability. Performance of current examples of this type can best be judged from the flight test results obtained by Zacher reported in (55).

General Aviation Aircraft: Light, powered aircraft cover a wide range of size, shape and performance, although the criticism has been leveled that the basic technology of the field has not changed very much in the last twenty years. Progress is being made in several areas, however, including provision of STOL capabilities in some types. Almost any general aviation reference (e.g. Jane's All the World's Aircraft) contains extensive data on machines in this category.

Quantitative Comparisons

The quantitative comparisons made in this study involve three basic areas: geometric size/weight, steady level flight performance (e.g. speed, glide angle), and power/energy consumption.

Performance: The dominant fluid dynamic scale parameter in low-speed flight is the Reynolds number (based here on average wing chord and average resultant speed or simply flight speed depending on whether the device is gliding or flapping its wings). The range of average Reynolds number versus flight speed for some typical insects through light powered aircraft is shown in Figure 6. The significance of Figure 6 is enhanced by consideration of basic airfoil performance as a function of Reynolds number. Figure 7 shows the variation in maximum section lift-drag ratio over the range $10^2 < Rn < 10^7$ for a variety of laminar and turbulent airfoils beginning with the well known data of Thom and Swart (58). It is important to note that due to laminar separation the performance of the smooth airfoils of conventional contour deteriorates violently below Rn values in the region of 10^5. The classic reference on airfoil characteristics in this range is the book by Schmitz (59). Other trends in airfoil performance with Reynolds number are a general decrease in maximum section lift coefficient and increase in drag with decreasing Rn values. The general problem of airfoil performance at Rn values below about 7×10^5 and in unsteady flow (representative of flapping flight) has been relatively poorly investigated and a good deal of clarification is still required. A representative sampling of low-speed airfoils for various applications is shown in Figure 8.

Of major interest in this survey is the relative gliding performance of low-speed fliers. Figure 9 is a sample of various test and analytic results, presented in the usual sailplane format (i.e. sink rate versus horizontal speed) for flight in still air under standard sea level conditions.

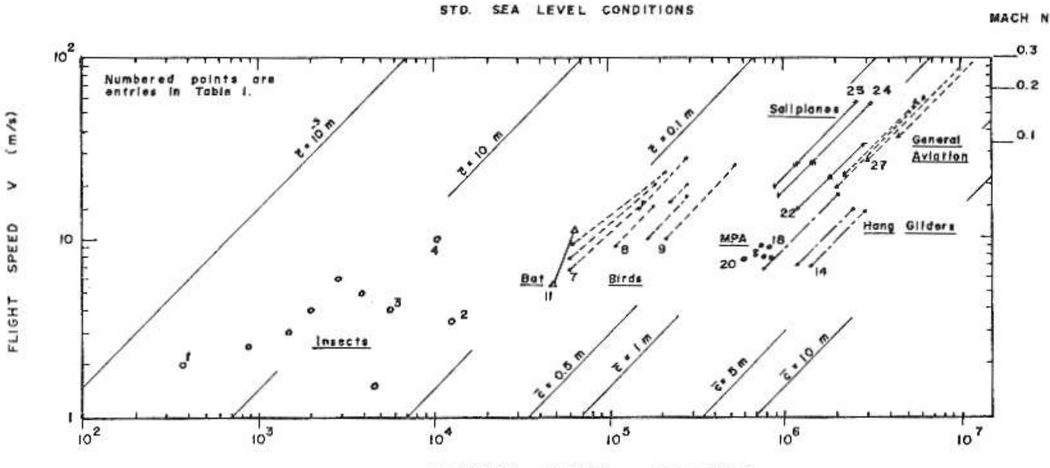


FIGURE 6. Variation in Average Wing Reynolds Number with Flight Speed

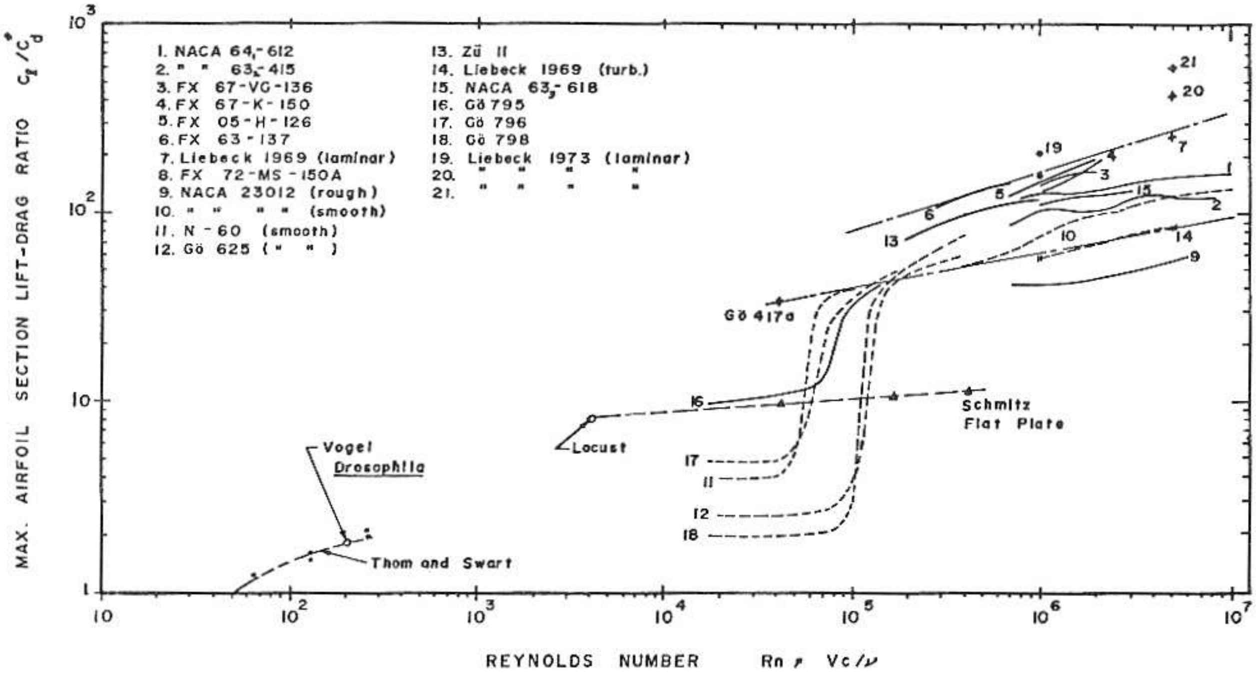


FIGURE 7. Variation in Maximum Airfoil Section Lift-Drag Ratio with Reynolds Number

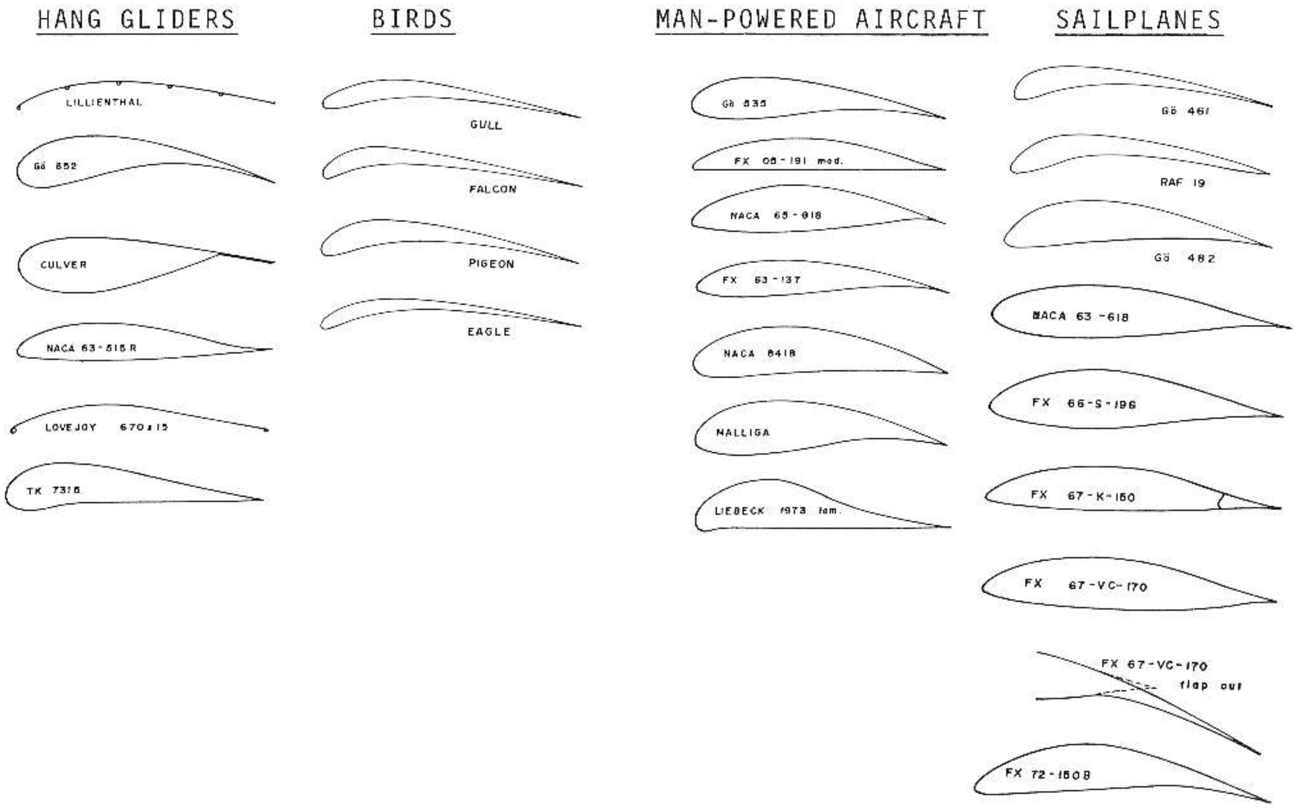


FIGURE 8. Representative Low-Speed Airfoils

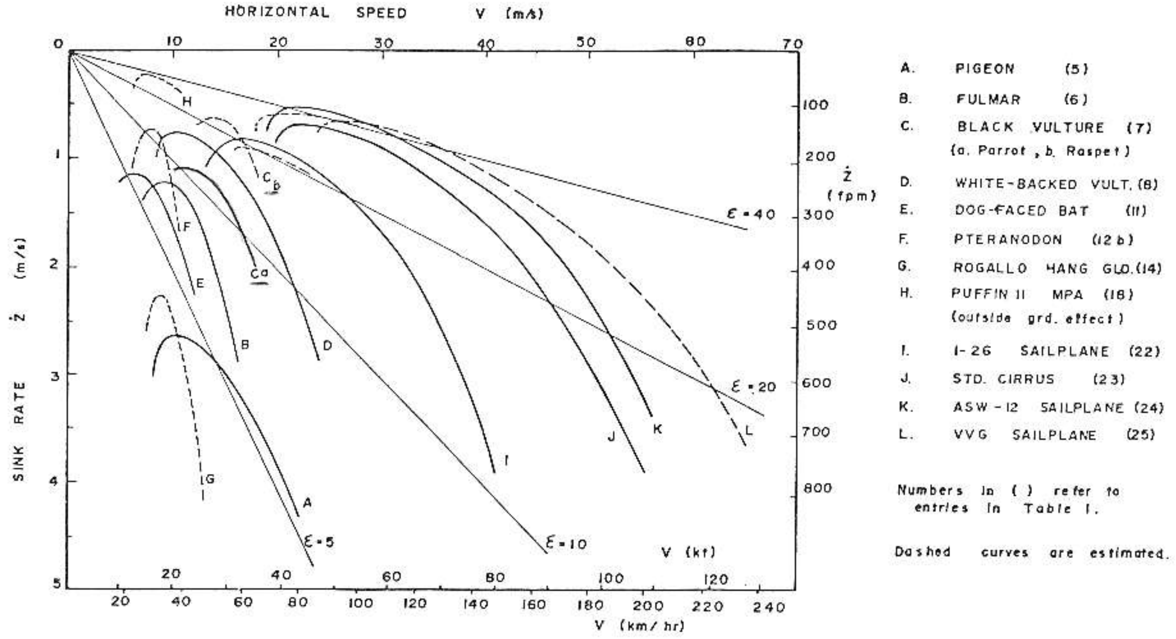


FIGURE 9. Still Air Sea Level Glide Polars for Several Natural and Man-Made Flying Devices

Size and Weight: With the publication of the massive compilations by Greenwalt (8) and Hartman (9), a large body of data now exists on the relation between geometric size (wing span and area, aspect ratio, tail area, etc.) and weights (gross, wing, muscle and internal organ) for nearly the entire range of animal fliers. This basic data can be supplemented by the huge body of data available on man-made aircraft in the many standard aeronautical references cited previously, to provide a comprehensive survey of the full range of flying devices. Using Greenwalt's format as the basis, the variation in wing span and wing area with loaded mass for the range of devices listed in Table 1, are presented in Figures 10 and 11. The considerable relative uniformity of the data for birds and bats contrasts with the substantial scatter of the data for insects, each of these groups representing viable forms of flying machine. The apparently anomalous behavior of the data on hummingbirds and man-powered aircraft should also be noted.

Energetics: In the general study of "transportation" systems, no single simple index can provide a complete measure of the relative "cost" of operation of devices as dissimilar as cows, submarines and sea gulls. Of major importance in the study of the relative efficiency of all types of locomotion, however, is the amount and rate of energy consumption required to sustain it. Several authors, notably Gabrielli and von Karman (7) and Tucker (26, 28, 29), have extensively employed the basically non-dimensional index "energy consumed per unit weight per unit distance traveled", in studies of the different modes of travel. In the case of steady motion, this index becomes:

$$(1) \quad \phi = \frac{E}{WR} = \frac{E/\tau}{W \cdot R/\tau} = \frac{P}{WV}$$

The index ϕ proves to be an effective comparison parameter, provided care is taken in defining the constituent terms in the index and uniform comparisons are made. For example, care must be taken when comparing natural and man-made devices to define which values of power are being used; whether net or external. The general relation between the two is:

$$(2) \quad P_n = P_e/\eta + P_o$$

Aircraft (with the possible exception of man-powered types) do not have a "basal metabolic rate" (P_o) and the net "propulsive efficiency (η) for, say, an internal combustion engine/propeller system, accounting for both the propeller efficiency and the thermal efficiency of the unit, may be substantially different from that of the flight muscles of a bird. In comparing flying systems in steady level flight, the index ϕ has the additional significance:

$$(3) \quad \phi_e = \frac{P_e}{WV} = \frac{TV}{WV} = \frac{D}{W} = (L/D)^{-1}$$

From eqn. (3) it is clear that comparisons of flying devices are only meaningful if the criteria for calculating ϕ are uniform (i.e. condition of maximum L/D, minimum power required, maximum power available, etc. and the corresponding speed at which it occurs). Further, one must always keep in mind that the devices being compared may have been "designed" for very different operational requirements (e.g. pigeons and jet transports). Despite these qualifications and limitations, the ϕ parameter can be a useful basis for limited "economic" comparison.

Following Tucker (26, 28) and using data from Table 1, values of minimum (optimum) net transportation economy (ϕ_n^*) as a function of loaded weight (half fuel weight for powered aircraft) are shown in Figure 12. The points in Figure 12 representing Gen. Av. aircraft are based on cruise fuel consumption rates at the condition of L/D max. at sea level assuming the fuel has an energy content of

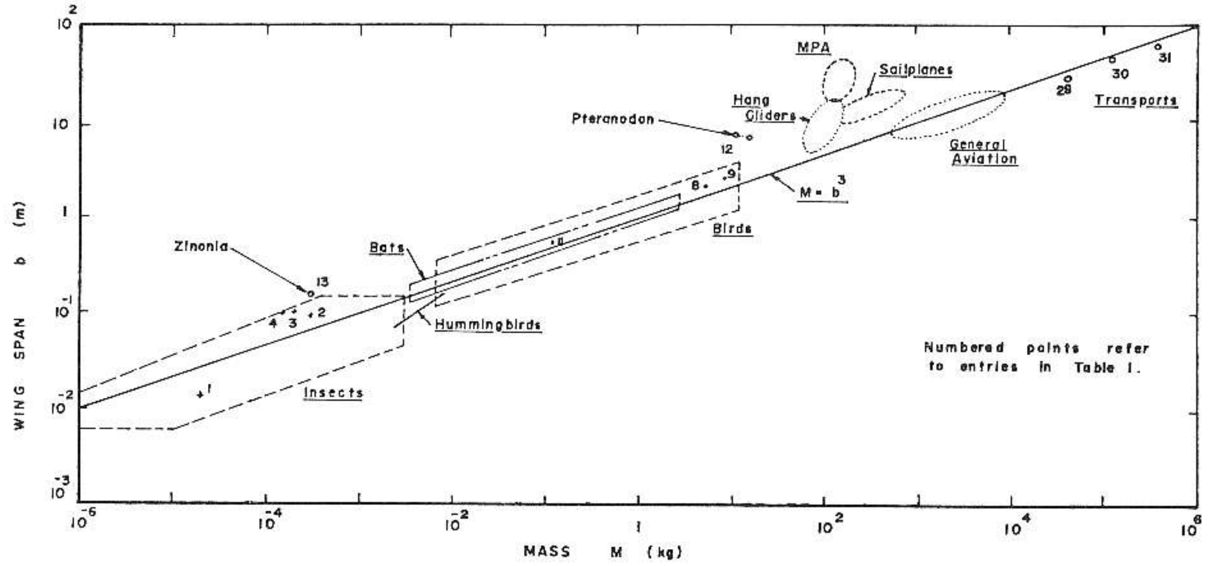


FIGURE 10. Variation in Wing Span with Loaded Mass

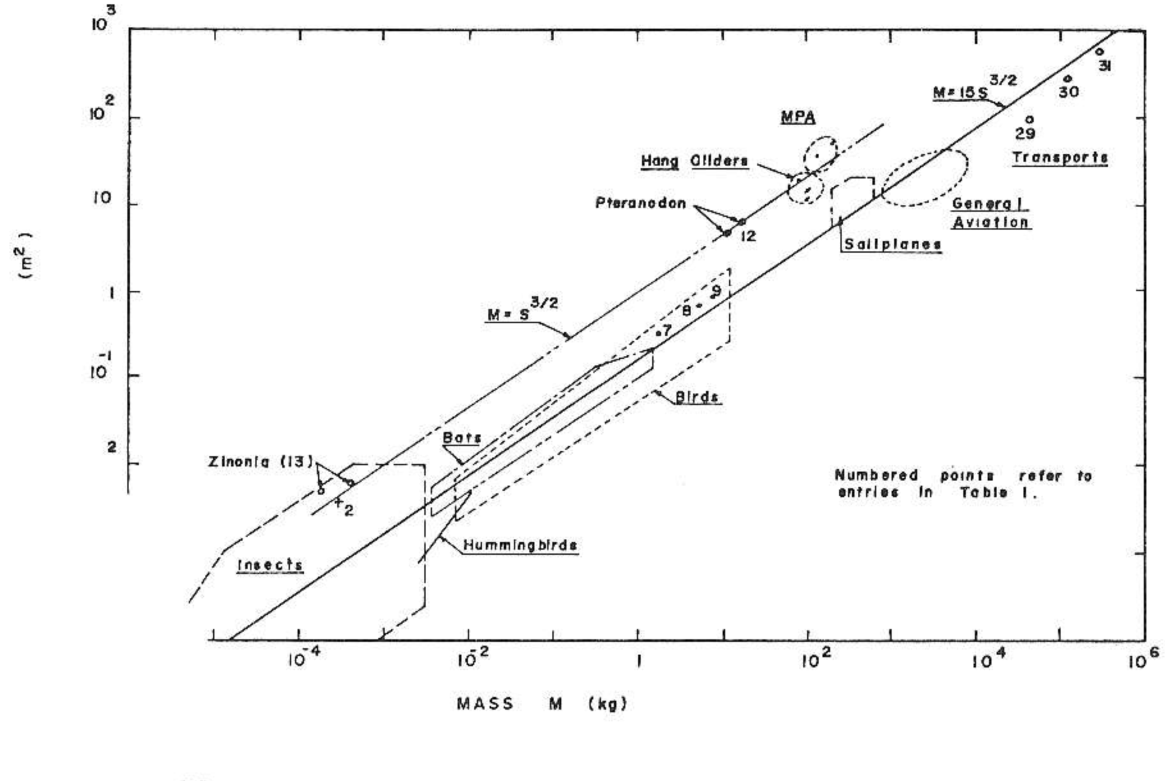


FIGURE 11. Variation in Wing Area with Loaded Mass

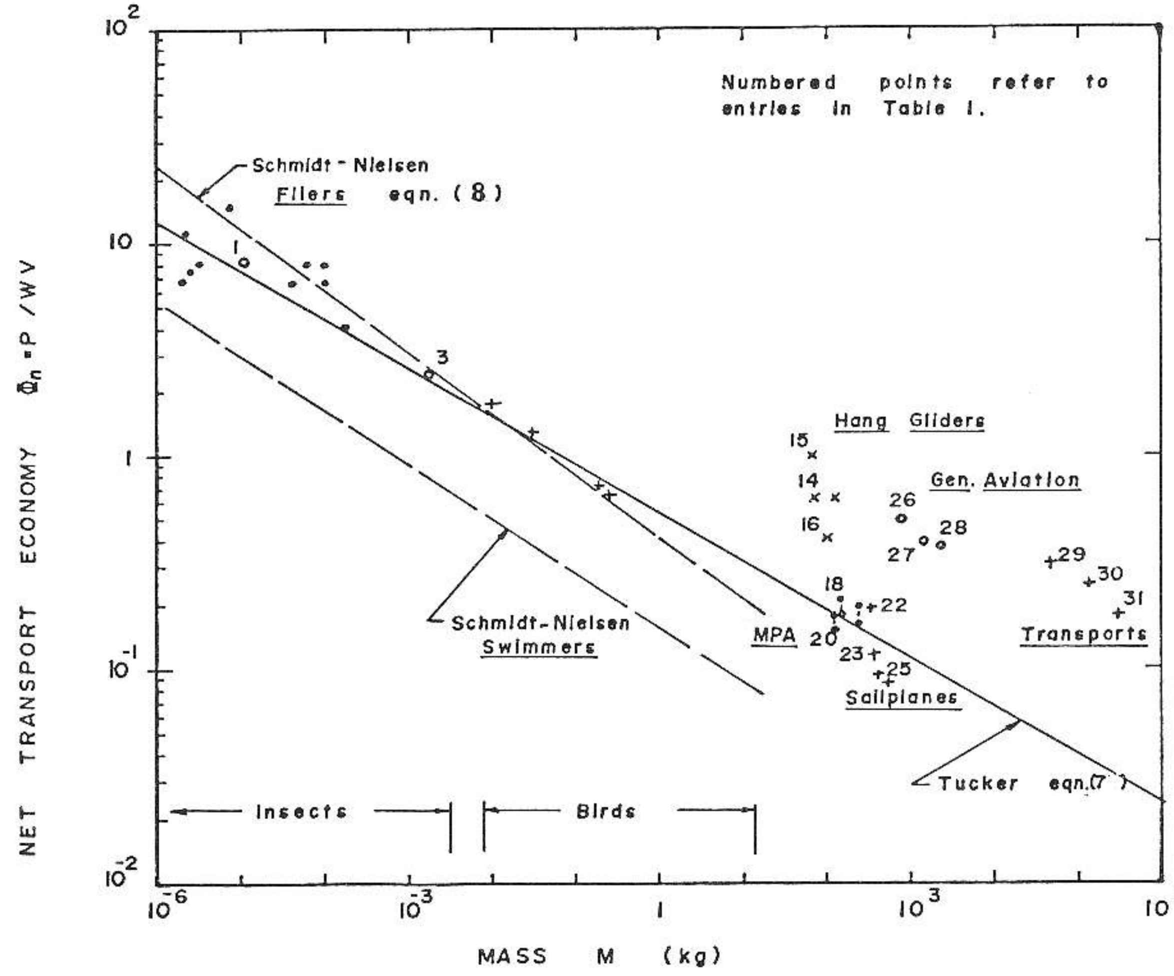


FIGURE 12. Variation in Minimum Net Transport Economy with Loaded Mass

10,300 Kcal/kg. Equivalent data for sailplanes has been constructed by assuming each is fitted with a dragless, weightless powerplant with the same net efficiency as those in the Gen. Av. machines. For general comparison, the corresponding curves from Schmidt-Nielsen (10) for swimmers (fish) and birds/insects are indicated. Comparisons based on minimum (ϕ_e^*) are presented in Figure 13 where η for bird flight muscles is assumed to be 20% (28). The basal metabolism rates for the birds and man are taken (where other data are unavailable) from Lasiewski and Dawson (60). These values are:

(4) $P_o = 6.15\ m^{0.724}$ passerine birds

$P_o = 3.73\ m^{0.723}$ non-passerine birds

$P_o = 3.36\ m^{0.734}$ mammals (except bats)

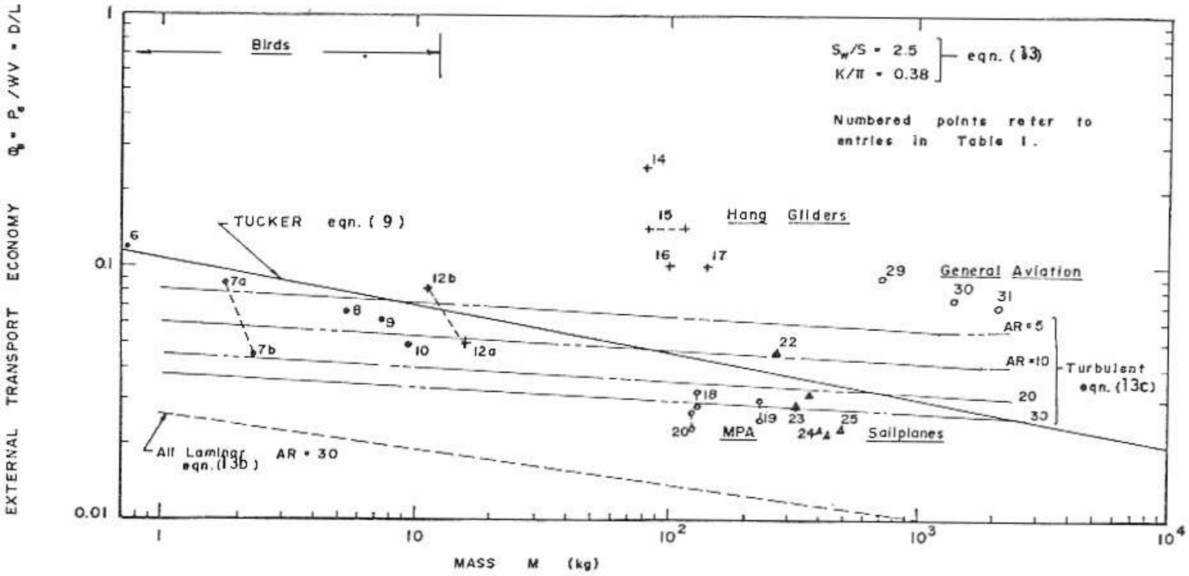


FIGURE 13. Variation in Minimum External Transport Economy (Drag-Lift Ratio) Loaded Mass

Analysis and Discussion

The combination of Figures 9 through 13 present a general overview of the relative size and "cruise" performance. Several volumes would be required to analyze in detail the similarities and differences in these devices and correlate size, shape and performance with the specific operational requirement each is intended to satisfy. Much of the basic data for such a study does not yet exist or is at best incomplete.

Two simple analyses of the data presented in this survey are of interest. The first is to examine the consequences of the square-cube law and to compare these with the data in Figure 10 and 11. The second is to attempt to theoretically verify the statistical relation due to Tucker (26) shown in Figure 12.

Square-Cube Law: A common approach to evaluating data like that presented in Figs. 10 and 11 is to apply the simple "square-cube law" the foundations of which were set by the aviation pioneer Cayley. A good critique of this simplistic but effective "law" has been provided by Cleveland (2). The square-cube law states that the surface area and weight of geometrically similar objects increase as the square and cube of some characteristic linear dimension respectively. Application of such a rule to complex objects like flying machines, even when geometrically similar, is of questionable validity.

The basic law specifies:

$$(5) \qquad b \sim \ell \qquad\qquad W \sim W$$
$$S \sim \ell^2 \qquad \text{or} \qquad S \sim W^{2/3}$$
$$W \sim \ell^3 \qquad\qquad b \sim W^{1/3}$$
$$AR = \text{constant} = b^2/S$$

The general trend in the data in Figure 10 and 11 is in rough agreement with the square-cube predictions:

$$(6) \qquad b = M^{1/3}$$
$$S = 0.165\ M^{2/3}$$

A similar "eye-ball" fit of similar data by Schmidt-Nielsen (10) gave:

$$(10)\quad \Phi_n^* \sim W^{-0.293}$$

Using Tucker's procedure (28), eqns. (2) and (46) and $\eta = 0.2$, the corresponding Φ_e^* value based on eqn. (9) is:

$$(11)\quad \Phi_e^* = (L/D^*)^{-1} \sim W^{-0.185}$$

According to the simple square-cube (without account taken of Rn scale effects), the quantity P/WV should be constant. The following simple analysis sheds some light on this discrepancy and on Figures 12 and 13 in general.

Assume the drag of the vehicle can be expressed approximately by:

$$(12)\quad C_D = \frac{D}{1/2\,\rho V^2 S} = C_{Do} + \frac{KC_L^{\,2}}{\pi\,AR}$$

$$C_{Do} = Ko\,\overline{Rn}^{\;-a} \quad (Sw/S)$$

$$\overline{Rn} = \frac{V\bar{c}}{\gamma}$$

then in steady, level flight $(T \cong D,\ L \cong W)$:

$$(13)\quad \Phi_e = \frac{Pe}{WV} = \frac{T}{W} = \frac{D}{L} = \frac{C_D}{C_L} = \frac{C_{Do}}{C_L} + \frac{KC_L^{\,2}}{\pi\,AR}$$

$$V = \left[\frac{2W}{\rho C_L S}\right]^{\frac{1}{2}}$$

$$C_{Do} = K_o\,\overline{Rn}^{-a} \quad (Sw/S)$$

$$\overline{Rn} = \frac{V\bar{c}}{\gamma} = \frac{VS}{\gamma b} = \left[\frac{2}{\rho\gamma^2}\right]^{\frac{1}{2}} \left[\frac{W}{C_L\ AR}\right]^{\frac{1}{2}}$$

thus:

$$(14)\quad \Phi_e = C_1\,C_L^{(a/2-1)}\left[\frac{AR}{W}\right]^{a/2}\left(\frac{Sw}{S}\right) + C_2\,\frac{C_L}{AR}$$

$$C_1 = K_o\left(\frac{\rho\gamma^2}{2}\right)^{a/2},$$

$$C_2 = K/\pi$$

The optimum value of Φ_e can be found very simply by differentiation of eqn. (14) or more elegantly by a trivial application of geometric programming (61). The general result is:

$$(15)\quad \Phi_e^* \sim \left(\frac{Sw}{S}\right)^{2/4-a} AR^{-2}\left(\frac{1-a}{4-a}\right) W^{-a/4-a}$$

To test this result, consider the numerical values corresponding to various scaling models (i.e. drag scales as a laminar and turbulent flat plate and there is no Rn scaling):

$$(16)\ (a)\quad \Phi_e^* \sim \frac{Sw}{S}^{\frac{1}{2}}\,AR^{-\frac{1}{2}} \quad \text{(no Rn scale, a=o)}$$

$$(b)\quad \Phi_e^* \sim \frac{Sw}{S}^{4/7}\,AR^{2/7}\,W^{-1/7}$$

(lam. flat plate, a = 1/2)

$$(c)\quad \Phi_e^* \sim \frac{Sw}{S}^{10/19}\,AR^{-8/19}\,W^{-1/19}$$

(turb. flat plate, a = 1/5)

Numerical values of eqn. 16 assuming std. sea level conditions, Sw/S = 2.5 and $K/\pi = 0.38$ are plotted in Figure 13. The values obtained with the assumption that a = 1/5 (turb. flt. plate) are seen to be in good agreement with the soaring <u>bird</u> data in Table 1. Results similar to those in eqn. (16) can be obtained directly from the square-cube law analysis by assuming a constant value of aspect ratio and the scaling laws specified. It is tempting to extend the analysis by adding a constraint involving

Several entire classes of device (e.g. insects) are widely scattered about this average of (e.g. MPA's) cluster far from the average. The overall success of the simple law in predicting the basic trend indicates that the rule has some merit, however. Much of the deviation and scatter can be attributed to a combination of operational, structural and performance requirements which make strict comparison subject to numerous qualifications. It is interesting to note that the points representing butterflies, zinonia, Pteranodon and hang gliders all tend to fall along the square-cube line $S = M^{2/3}$. Similar lines can be drawn connecting sea soaring birds and sailplanes, and bees, pigeons and light aircraft. Further, the large deviation of the MPA group from the average is partly explained by the fact that these machines are designed with extremely low load factors (usually on the order of 2) and fly at extremely low speed in "no wind" conditions very close to the ground. There is no apparent natural counterpart to the MPA. The defeat of the square-cube law in the case of large transport aircraft is well discussed by Cleveland (2).

The un-constrained square-cube law predicts that wing loading (W/S) should scale as the cube root of the weight. Greenwalt's data support this in general and Pennycuick's data on soaring vultures (23,24) support this variation in remarkable detail. Greenwalt also shows that wing weight for natural fliers varies as $S^{5/3}$ with surprisingly little scatter. The consequence of this can be shown as follows:

$$(7) \quad W_w = \text{wing weight} \sim b\bar{c}\bar{t} = S\bar{t}$$

$$W_w \sim S^{5/3} \quad \text{(Greenwalt)}$$

Therefore, we conclude:

$$(8) \quad \bar{t} \sim S^{2/3} \sim W^{4/9}$$

$$\bar{t}/\bar{c} \sim S^{1/6} \sim W^{1/9}$$

It can be readily shown (2) that increase of the thickness/chord ratio with weight to the 1/9 power is exactly the condition required to keep the angular deflection of the wing constant if the skin thickness of the wing "torsion box" varies according to the square-cube law (i.e. to the cube root of weight). Further mechanical consequences of the square-cube law are described in (2, 6, 8, 18, 20).

Analyses of the performance consequences of the square-cube law are often marred by lack of accounting for fluid dynamic scale effects. For example, with no account taken of Rn scaling, the law specifies that at a given (constant) lift coefficient, the level flight speed which is proportional to the square root of the wing loading should thus scale as the 1/6 power of the weight. Pennycuick (20) presents data on birds roughly supporting such a rule. He then shows that the power required for level flight varies with weight to the 7/6 power. Hartman (9) and Greenwalt (8) both show that the flight muscle weight of various types of birds is a nearly constant percentage of their total weight. Thus, since power required varies as the 7/6 power of weight, but power available only increases directly with weight, the maximum mass a flying bird (or animal) can attain is definitely limited (to about 12 kg according to Pennycuick's estimates). However, specialization of the structure to maximize soaring ability, for example, might allow this limit to be raised to that of the estimated 20 kg of the Pleistocene vulture Teritornis merriami. For a variety of reasons these limits do not necessarily apply to the case of human powered flight (20, 52).

Optimum Energetics: Tucker (26) has found that, on the basis of a limited amount of data, the minimum Φ_n^* for flying animals appears to scale according to the relation:

$$(9) \quad \Phi_n^* = 0.898\, W^{-0.227} = \frac{Pn}{WV}$$

weight/aspect ratio relations to eqn. (14) and thus obtain eqns. like (16) with only weight and area ratio appearing explicitly. Such an analysis has been attempted but appears unjustified with the present simplistic model because it contains no statement of operational requirement (specifically, it cannot differentiate between the geometries of birds like the albatross and the vulture). The following conclusions can be drawn from eqn. (16) and Fig. 13 however:

1. None of the eqns. (16) predict the W exponent -0.185 resulting from Tucker's analysis, however eqn. 16c fits the soaring bird data, presented in Table 1 when realistic values of Sw/S and K are used. The bird data in Table 1 also fall within the standard deviation of Tucker's statistical analysis.

2. Without data on the <u>gliding</u> performance of insects, it is not possible to test eqn. (16) against Tucker's statistical fit in this region. A value of Sw/S quite different from 2.5 is required to "describe" insect geometry.

3. The values of Φ_e^* predicted by eqn. 16 do not agree with the sailplane points. The sailplane data indicate that sailplenes scale according to some value of <u>a</u> intermediate between a turbulent and laminar flat plate. This is to be expected since sailplanes are the one type of machine over which substantial regions of laminar flow can exist.

4. In connection with (3) above, it is probable that eqn. 16(b) has meaning only over the range $10^5 < \overline{R}n < 3 \times 10^6$ corresponding to $1 kg < M < 10^3 kg$ (depending on aspect ratio).

   The curve corresponding to AR = 30: eqn. 16(b) in Figure 13 can be interpreted as the approximate lower bound of flying devices of reasonable geometry whose boundary layer is entirely laminar.

5. Simple statistical data fit like eqn. (9)-(11) explain very little by themselves and analyses which ignore fluid mechanical scaling effects and operational considerations may be incorrect and/or misleading.

Three final observations based on Figures 9, 12 and 13 can be made:

1. Hang glider performance has not begun to approach its theoretical potential. The degree to which economic and other operational considerations may hinder fulfilling this potential is unclear at present. The example of <u>Pteranodon</u> is encouraging, however.

2. Both Figure 12 and 13 indicate that MPA designers have done a remarkably good job of meeting extraordinarily difficult design requirements and limitations. Present MPA's appear to operate, on an energy consumption basis, about as well as could be hoped. The geometric penalties involved are well demonstrated by Figures 10 and 11, however.

3. General Aviation aircraft appear to be unnecessarily inefficient judged by the criteria used in this survey.

Conclusions

This paper has presented a brief survey of the geometric and energetic characteristics of a range of flying devices covering twelve orders of magnitude in weight. It has been shown that there is substantial general pattern and order in the data presented, however, there exist at least as many detailed differences and anomolies between various types of flying device as there are similarities. The picture presented remains, in many particulars, incomplete and/or inconclusive. One factor appears clearly, however: Explanations of flight phenomena based on analyses which do not account for the coupling between aerodynamics (fundamental fluid mechanics), structural and material characteristics, and operational requirement and constraints are not adequate.

Nature continues to be a rich source of inspiration to the designer and engineer - particularly to those in the field of ultra-light aeronautics. It has been a major goal of this survey to present an introduction to a broad range of information which may be of value in future research.

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ADDENDUM

Since the preparation of this paper, two major publications on Pterosauria have appeared which, while not seriously altering any of the above material, add very significantly to knowledge about this poorly understood branch of natural flight.

1. Bramwell, C. D. and Whitfield, G. R., "Biomechanics of Pteranodon", Phil. Trans. R. Soc. London B, Vol. 267, 1974, pp. 503-581. This reference has an excellent bibliography.

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