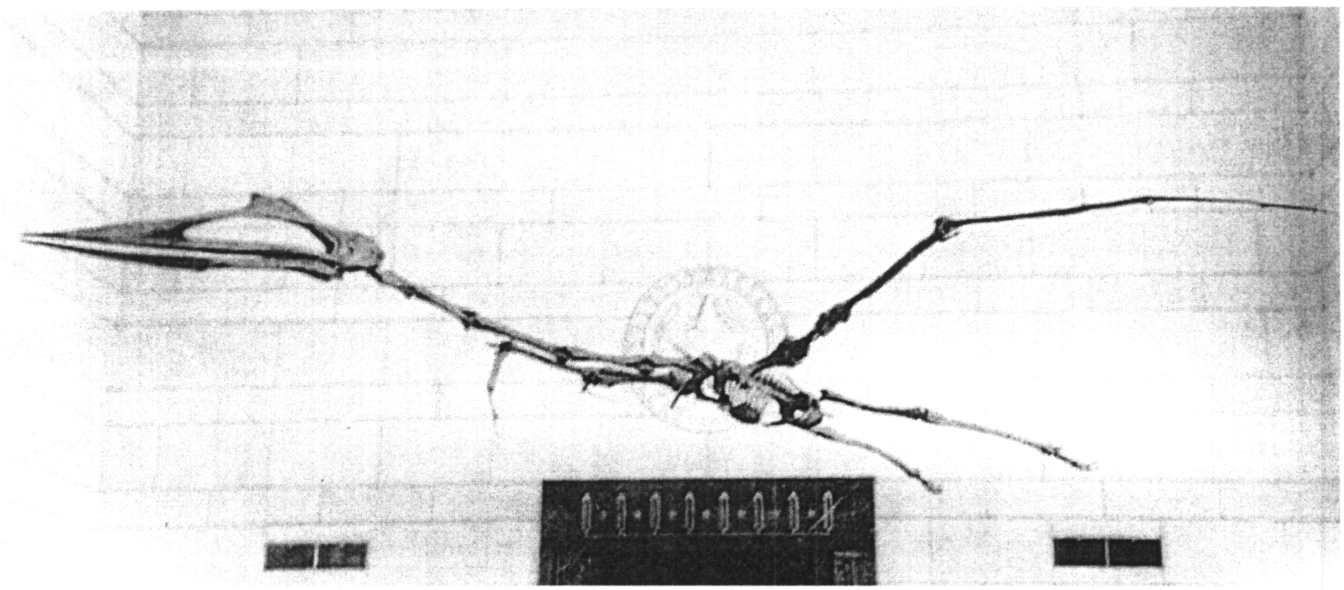
WINTER 2000

# Flapping Wings

THE ORNITHOPTER SOCIETY NEWSLETTER



# Quetzalcoatlus

## Nature's Largest Flying Machine

*by James Cunningham*

Sixty five million years ago, near the end of the Cretaceous period, the geography and climate of North America were quite different from their modern appearance. Average temperatures were a few degrees higher (possibly as much as 4° Celsius or 7° Fahrenheit), perhaps due to the higher carbon dioxide content of the atmosphere and a somewhat different configuration of the continents and oceans.

The oxygen content of the air seems also to have been about 25% greater than now, so the atmospheric density was slightly higher, and consequently, flying speeds may have been as much as 10% lower than they would be in the modern atmosphere. However, the assumption that any animal capable of flight during the Cretaceous would also be capable of flight today is quite reasonable.

At that time, North America was still split by a receding shallow sea, which ran north through eastern Texas. The isthmus of Panama did not exist, making South America a huge island. The presently rugged Big Bend area of west Texas was a broad, gentle plain about 320 km (200 miles) west of the Cretaceous sea, with mild slopes and meandering streams. But it was not a grassland or prairie, as grass had not yet evolved. It is a characteristic of gently meandering streams in sedimentary soils that the banks are often slightly higher than the surrounding floodplain, and occasionally these streams overflow their banks and inundate the adjacent floodplain. When the floodwaters recede, the high overbanks impede the water reentering the stream and long, shallow overflow lakes are temporarily left behind. This is a process that continues today and is common in the relatively flat lands of Arkansas and Mississippi near the Mississippi River. The temporary lakes can be rich with fish and become quite crowded as the long, narrow pools dry up after the rains. Birds flock to these small lakes to feed now, as they and other wildlife did during the time of the dinosaurs. Two of the animals that used those lakes sixty five million years ago were the last known pterodactyls, a type of short-tailed pterosaur.

Pterosaurs first appeared in the fossil record about 210 million years ago, small actively flying vertebrates with long tails. They were distant relatives of crocodiles, dinosaurs, and birds, but quite distinct from the other three groups. They were not feathered; some may have had a fur-like covering over part of their body. The earliest pterosaur fossils already had all of the features required for flight expressed in their skeletons, and all pterosaurs maintained essentially the same pattern with only limited changes over the ages. Before they disappeared from the fossil record at the end of the Cretaceous, they had become much larger. As they became more dependent on active flight control, they lost their tails and the length of their necks and heads increased. But in general appearance, the latest pterosaurs still looked much the same as the earliest known examples. There is no evidence of gliding ancestors, and it is speculated that these animals launched into active flight by leaping from the ground rather than gliding from trees. They actively flapped until they achieved an appropriate speed and location for soaring flight.

The remains of several pterosaurs have been found with the wing membrane preserved. In planform, the wings of the larger pterosaurs were long and narrow, reminiscent of albatrosses. The wing membrane (patagium) was flexible like the membrane of a bat's wing, but flight loads were handled differently and there were few similarities in structural design. In the large pterodactyls, there is no evidence of a wing attachment to the legs. The legs carried a separate membrane (uropatagium) contiguous with the tail. The leg/tail/uropatagium complex formed a widely-spread aerodynamic tail structure reminiscent of an inverted-V-tail Bonanza, and this structure provided primary yaw control, glide slope adjustment, and may have supported most of the weight of the legs at intermediate flight speeds. Inboard of the elbow, the trailing edge of the wing membrane overlapped the thigh, so that the innermost wing and leg formed a slotted Fowler flap.

The Big Bend pterosaurs were called *Quetzalcoatlus* species and *Quetzalcoatlus northropi*, very similar animals except for size. *Q* species was a large animal, weighing perhaps 20.5 kg (45 pounds), with a wingspan of almost 5 meters (16 feet). The span was almost 50% greater than *Diomedes exulans*, the largest living albatross. Only two flying birds are known to have been larger than *Q* species. One was a pseudodontorn [named for the sharp, tooth-like projections in its beak], *Pelagornis*, with a wingspan of about 6.2 meters (20-21 feet). The other was the teratorn [a group of condor-like birds], *Argentavis*, with a wingspan of perhaps 7.3 meters (24 feet). In all of history, perhaps only five or six species with a larger wingspan have ever flown. Two of those were the pterosaurs *Pteranodon longiceps* and *P sternbergi* at 6.8 meters (22-23 feet), a larger pterosaur from Jordan, *Arambourgiania*, at perhaps 10 meters (32-33 feet), estimated from a very speculative size projection based upon a single neck vertebra, and a recently discovered pterodactyl from South America which may rival *Q northropi* in size.

With the possible exception of the new find, *Q northropi* dwarfed the others and could shade *Q* species under one of his wings. *Q Northropi* had over twice *Q* species' wingspan, almost 11 meters (36 feet). His head was 2.1 meters long, his neck 3.3 meters. The distance from his hips to his ankles was more than a man's height, and when standing on the ground his shoulders were nearly 3 meters in the air. In flight, he measured well over 6 meters from the tip of his toes to the tip of his beak. At the elbow, his wing was 25 cm thick. In gross dimension, this animal was similar to the Carbon Dragon and other ultra light sailplanes. Though large, his torso measured only 80 cm from hip to shoulder.

Early estimates of his weight were as low as 64 kg, but preliminary calculations indicate that a weight 160 kg could be carried quite comfortably. Greg Paul, a paleo researcher and artist who does very sound work, believes *Q northropi* may be as much as a 40 kg heavier, approaching 200 kg.

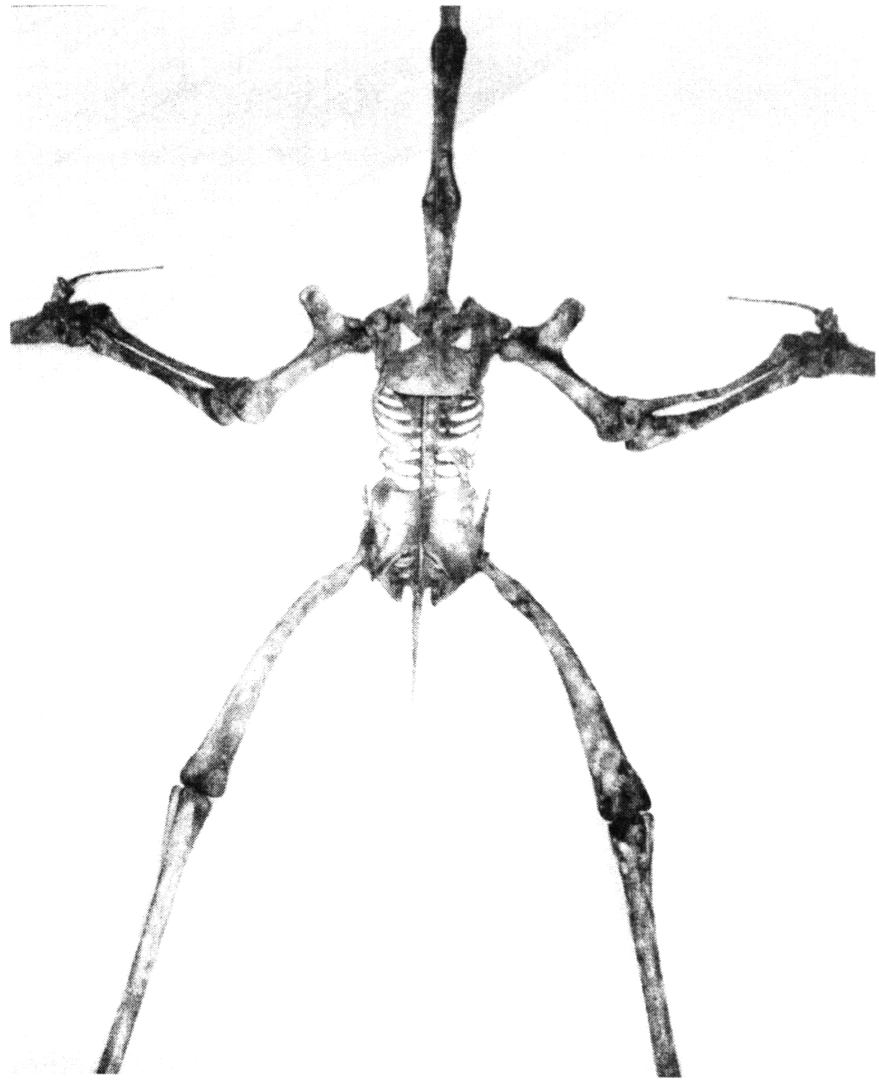
In 1971, Douglas A. Lawson was working near the Rio Grande, in Big Bend National Park in Brewster County in southwestern Texas. His intent was to learn more about the ecology and environment of the last dinosaurs, and the Big Bend is one of a limited number of places on earth where the Cretaceous/Tertiary boundary (K/T boundary) is exposed and conditions are appropriate for that type of study. Lawson was working in a valley of the dry badlands when he found pieces of bone that had washed down from the hillside above. He removed a part of the fossilized bone and returned to Austin, where his advisor, Dr. Wann Langston, Jr., identified it as a very large pterosaur. They returned to Big Bend to attempt to salvage the entire animal, but only about 40% of the left wing remained. Since that time, the original materials have been in the custody of the Texas Memorial Museum and Langston at UT Austin.

In the following years, Dr. Langston and others continued to search through the Javelina Formation. In 1973, Mr. William Amaral found additional remains, a group of much smaller, but otherwise remarkably similar animals that had died together, a few miles from the original site. These smaller remains, *Q* species, were derived from a limited area termed the Amaral site. There are perhaps as many as ten individuals present, with no significant differences in size, and all material represents animals with wing spans of about 5 meters, roughly half the size of *Q northropi* at 11 meters. The *Quetzalcoatlus* collection is deposited at the Texas Memorial Museum in Austin, Texas.

Many pterosaurs possess sagittal cranial crests on the skull. The sagittal crest of *Q* sp. differs from all others regarding its position above the posterior part of the nasoantorbital fenestra (the opening for the nostril in front of the eye). The skull is long and slender. The lower jaw can be opened to make an angle of just under 52 degrees with the upper mandible, and the hinges are constructed so that the jaw spreads at the rear as it is opened. The lower jaw contains attachment markings for a throat pouch, and the longitudinal profile and cross section of the mandible show hydrodynamic modifications that suggest the animal fed by fishing on the wing, a skimmer cruising in ground effect.

Unlike other piscivorous pterosaurs, *Quetzalcoatlus* did not live near the sea. They lived in the environs of substantial river systems adjacent to flood basins and died at the margin of a shallow, fresh-water lake. They were equipped to cover vast regions to acquire food, and adequate resources were available to them in overflow lakes and the broad alluvial plains that were the focus of Javelina deposition.

*Quetzalcoatlus* species and *Quetzalcoatlus northropi* belong to a family of long necked, chunky pterosaurs called azhdarchidae. Cranial materials from these pterosaurs are rare, and it is difficult to securely establish the relationships of *Q* sp. and *Qn*. But *Q* sp. does share one remarkable cranial feature, the low position of the orbit in the skull, with tapejarids, another pterosaur family. This feature is unique to azhdarchidae and tapejarids, suggesting that they are sister groups. Differences between *Q* sp. and tapejarids include the contrasting skull lengths in front of the nasal opening. The tapejarids *Tapejara* and *Tupuxuara* are relatively short-snouted, while *Quetzalcoatlus* is long-snouted. Other minor differences and notable similarities exist. Azhdarchidae all share some unique features with the early Cretaceous tapejarids, and all have an intriguing mechanism in the outer wing that provides for automatic control of gust loads or other high-load factors.



Pterosaurs are unlike birds and bats in that their membrane wing does not contain internal bracing that can directly transfer torque from the flexible membrane into the skeletal spar. Therefore, they have developed an indirect transfer that is truly elegant in its simplicity. Pterosaurs load their wings like an inverted suspension bridge, with the flexible membrane replacing the roadway, and the skeletal spar and associated muscles and tendons replacing the suspension cable. In soaring flight, the wingtip is held approximately level with the shoulder and wrist, while the elbow, wrist, and wing finger pivot (in humans, the joint connecting the palm and little finger) are held higher. The wing membrane is span-loaded without a trailing edge tendon, and the lift loads generated in flight are primarily transmitted in a spanwise direction and loaded into the skeletal spar at the forearm. The skeleton of the outer wing functions a bit like a bow held horizontally, so that the increasing spanwise tension due to increasing flight loads draws the wingtip back. In the azhdarchidae, the second and third phalanges of the fourth digit (analogous to our little finger) have a tee-shaped cross section, with the bar of the tee on top and the stem hanging down.

As flight loads draw the wingtip back, the tee-shaped asymmetry makes the bottom of the wing more flexible in a fore-and-aft direction than the top is, so an increase in spanwise tension due to extra lift causes the skeletal spar to twist nose down while the wingtip rises. At this point two things happen. The twist sets the trailing edge of the wing higher than the leading edge, reducing the angle of attack, and the additional spanwise tension reduces the camber in the wing, consequently reducing the negative angle at which zero lift occurs. These two reductions in effective angle of attack, both acting together, reduce the coefficient of lift and unload the wing.

In early 1984, the Smithsonian's Air and Space Museum commissioned Paul MacCready and his firm Aerovironment, Inc. to build a half-scale flying replica of *Quetzalcoatlus northropi*, and Sam Johnson of Johnson Wax, Inc. concurrently sponsored construction of the replica and the production of the IMAX film *On The Wing*, which documents the correlations between the flight of animals and machines. The intent was for the replica to fly realistically, powered by thermal or ridge soaring and by active wing flapping. It was to be controllable in most flying conditions, and was to be able to climb at a reasonable rate under its own power after an assisted launch. The robotics required for self-launch were considered to be economically unfeasible at the time. To enhance realism and to facilitate the use of a quiet electric power system, no specific limits were set for the lower limit of powered flight. On July 9-10, 1984, a symposium was held at Caltech in Pasadena. The meeting convened with approximately 40 people present, each expert in one or more of the branches of paleontology, paleobiology, robotics, aerodynamics, and flight stability and control. The consensus was that it was indeed possible to construct a flying replica of *Quetzalcoatlus*, either full-scale for the smaller animal, or half-scale of the larger, and experiments were initiated with moderately sized (1/4 to 1/3 scale) radio controlled gliding models using wing sweep for pitch control.

First with conventional aircraft tails, then progressively increasing pitch control with wing sweep while simultaneously reducing the size and control authority of the conventional tail, the team set a goal of eventually eliminating the tail entirely. The design panel had suggested to Aerovironment, Inc. that *Quetzalcoatlus* flew with its legs retracted, and this meant that unlike other pterosaurs, the legs and uropatagium (the wing-like membrane attached to the legs and tail) did not form an aerodynamic tail structure. This resulted in a preliminary use of forward sweep with wash-in at the wing finger joint in an effort to achieve pitch stability. The first model had an inherently inefficient wing twist, so a radio control mechanism was added to twist the wings in a way that *Qn* might have used. These first efforts gave turn control through extreme adverse yaw, but provided only limited pitch control. Additional yaw control was added by using the head as a steerable forward fin.

From the model tests, it was determined that twist didn't give adequate pitch control authority, and that *Q* species and *Q northropi* probably used active wing sweep to achieve pitch stability and compensate for the inherent pitch instability. It was decided that the final replica would be called QN, and that it would be a stand-off scale replica of the animals. It was further acknowledged that the living animals might not be able to maintain active powered flight for an extended period, and that they probably derived a large fraction of their required energy for flight from the atmosphere. Because of increasing inertia in the longer wing, the flapping frequency for actively flying animals decreases as size increases, with the result that *Q northropi's* wings flapped approximately once every two seconds.

Since the power available from each pound of muscle mass is directly proportional to the frequency of contraction in the muscle, this also means that large animals develop less power per pound than smaller animals can. Therefore, the power-to-weight ratio of larger animals suffers, and eventually an upper limit is reached where an animal can no longer generate enough power to fly by active flapping.

Although *Qn* may be the largest creature ever to fly under his own power, he does not appear to have been at the upper limit for animal flight. For very short periods (as during launch), the required power was produced anaerobically, and could be quite high, being mainly a function of the weight of the muscle and its contraction frequency. In the longer haul, the energy had to be produced aerobically, and it was limited by the oxygen absorption rate in the lungs and airways, and by the transport ability of the circulatory system, which control the rate at which fat and oils can be burned. Large, actively flapping animals consume their stores of fat at a remarkable rate and are limited in their maximum range in a manner similar to powered aircraft. Consequently, all very large flying vertebrates minimize their fuel burn and extend their range by soaring. *Quetzalcoatlus* was no exception, incorporating features that allowed launch using anaerobic muscle fibers, together with specializations for effective cross-country soaring flight combined with feeding runs while skimming in ground effect.

Although *Quetzalcoatlus northropi* was a well-muscled animal weighing approximately 150 kg (a rough estimate because mass calculations aren't complete yet), it didn't have power enough to hover by means of flapping flight, or to launch by flapping. It didn't run effectively, nor did it appear to have aerobic capacity for extended flapping. However, it could have launched in a dead calm even in the modern atmosphere by leaping at about a 30-degree angle to the horizontal, generating initial power with the hind legs, while pre-loading the front legs into a position of adverse mechanical advantage. Late in the leap, as the hind legs extended, the front legs unloaded and began to power the leap, thus providing an average acceleration of just over 2 g to reach its steady-state stall speed of 42 to 48 before starting the first recovery stroke with the front legs, which became the wings as they unfolded. At that point, thrust from initial anaerobic flapping, followed by aerobic flapping, was able to accelerate the animal at about 0.1 g until it reached cruise speed at about 72 km/hr. The major skeletal reinforcing in the arm and shoulder is aligned with launch loads rather than flight loads, and his pelvis, hip, and ankle are designed for leaping.

The animal's soaring ability was extraordinary, equaling or bettering the albatross and approaching that of a frigate bird, about the same as a lightly-loaded manmade sailplane. However, note that the numbers quoted below are approximate, in that they incorporate the induced and profile drag of the body, wing, and leg/tail complex, but exclude the profile and induced drag of the head and neck, which were not insignificant. In the modern atmosphere, if one assumes that a 150 kg animal is flying at 72 km/hr while at a height above ground (HAG) of 3 m with a wing span of 10.86 m and an aspect ratio of 17.12, carrying about 15% of the body weight with the leg/tail/uropatagium complex carried at an anhedral of about 5 degrees (the legs constitute approximately 15% of gross weight), then the resulting sink rate is about 0.59 mps, giving a lift/drag ratio of about 34:1. Approximately 800 watts are required to maintain level flight. For this condition, the profile drag and induced drag of the wing are equal at 1.15 kg, while the profile drag of the tail complex is greater than the induced drag, at a ratio of 1.85 kg to 0.24 kg, so that the total drag is on the order of 4.4 kg. If the anhedral of the tail complex is increased to 45 degrees for glide path control, then the lift/drag ratio is reduced to about 21:1. Yaw authority was produced by dropping and extending one leg more than the other.

*Quetzalcoatlus northropi* and *Quetzalcoatlus* species were fascinating animals whose exquisitely preserved remains are capable of telling us more about animal flight and the diverse means by which it is accomplished. They deserve and will require many more years of study.

# Low-Wing Freebird 2

*by Nathan Chronister*

Has anyone thought about putting the crank above the wings in an RC ornithopter? Here are my thoughts, and I'd like to hear yours.

**Advantages:**

· Spar offset would not be needed, simplifying construction.
· Low thrust line might counteract the tendency to dive when power is increased.

**Disadvantages:**

· Increased ground contact with wings, or longer landing gear needed.
· Landing gear or skid may be more difficult to install.
· It looks ridiculous.

The landing gear problems might be circumvented by not using any. If there were no landing gear, could a low-wing ornithopter land safely?

Before leaving for work one day, I converted a Freebird 2 to fly as a low-winger. I calculated the required conrod length using FlapDesign (see OS web site), and before the screen saver came on I had performed the modifications and mapped out the flight characteristics of the new ornithopter. All I had to do was make new holes in the conrods, to effectively shorten them, and then bend the tail down instead of up.

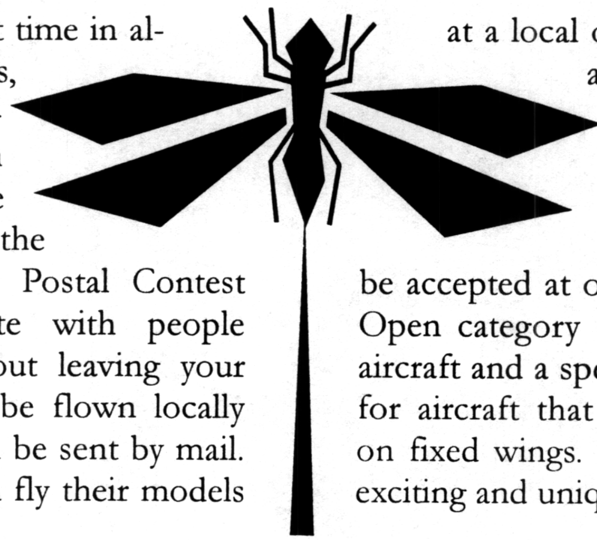
When I flew the low-wing Freebird, I was surprised to find a substantial tendency to climb and stall under full power but dive under low power. Many high-wing ornithopters show the opposite behavior, so the result had some precedent. Freebird 2 doesn't much have that problem though, and if anything, the CG should have been closer to the thrust line in the low-wing version. I wondered what was up.

The low-winger was very sensitive to tail position, which had to be set almost straight. The tail normally carries a negative load, and I figured the absence of that load was causing decreased stability and increased sensitivity to power level. I added two paper clips to the nose, and that helped. But why did I need to?

The answer may be as simple as the geometry of where the CG is relative to the wing. In flight, the wing is inclined to some positive incidence angle. For the low-winger, that shifts the CG aft. For the high-winger, it shifts the CG forward. If my explanation is correct, low-wingers will always need a more forward CG, which for rubber models means a shorter motor stick and decreased flight times. The forward CG is no problem for engine-powered ornithopters.

Even with the right CG, the low-winger will still have some tendency to dive when the power is low. I have begun to wonder if the power-on dive of high-wing ornithopters might actually be helpful in moderation, and therefore preferable to the low-wing configuration. My old electric ornithopter used to pitch up and slow itself down as it was coming to the end of its motor run, gracefully saving itself from the high speed dives the low-winger seems to exhibit. Maybe, like airplanes, ornithopters need a little down-thrust to fly right. If your ornithopter shows power-dependent characteristics, you might have to move the CG or you might have to change the dihedral angle.

# MILLENNIUM
# INTERNATIONAL ORNITHOPTER POSTAL CONTEST



This year, for the first time in almost two decades, builders of flapping-wing aircraft will have an opportunity to compete internationally. In fact, the Millennium Ornithopter Postal Contest allows you to compete with people around the world without leaving your own town. Entries will be flown locally and their flight times will be sent by mail. Typically, contestants will fly their models at a local or national indoor contest and have the local contest director sign the entry form to verify the flight times, but other forms of evidence may be accepted at our discretion. There is an Open category for any flapper-propelled aircraft and a special Flapper Lift category for aircraft that meet certain restrictions on fixed wings. We wish you luck in this exciting and unique competition.

## GENERAL RULES

- There is no entry fee.
- Each entry must include:

1. Entry form, completed and signed. The local contest director's signature is required unless the contestant provides other proof of flight duration (e.g., videotape) deemed suitable by OS postal contest director Nathan Chronister.
2. A scale 3-view drawing or clear 3-view photos of the model, with pertinent dimensions of model and motor.

- All entries must comply with the Design Requirements.
- The OS contest director has final authority to decide on compliance with rules.
- Flights must be made in the year 2000 and entries *received* by 15 Feb 2001. Send to Nathan Chronister, PO Box 376, Arkville NY 12406 USA.

## SECTION 1: TO BE COMPLETED BY CONTESTANT

Name: ______________________________

Address: ______________________________________________________________

Name and date of local event: _____________________________________________

Organization sponsoring local event: ______________________________

Name of local contest director: ______________________________

☐ Category A (open) ☐ Category B (flapper lift)

## SECTION 2: TO BE COMPLETED BY LOCAL CONTEST DIRECTOR

I certify that the contestant named above flew an ornithopter (flapping-wing aircraft) for a duration of ____ minutes and ____ seconds, and that the same ornithopter met the Design Requirements below. Signature: ___________________________ Date: _________

## DESIGN REQUIREMENTS

- An eligible model is propelled solely by flapping wings or small flapping fins.
- Models must be flown indoors and launched by hand within two meters of the floor.
- Power must be provided by a rubber motor.
- If the entry is for *Category B*, the following *additional requirements* must be met:
  - All non-flapping lifting or stabilizer surfaces must be aft of the rear motor hook. This applies to stabilizers, fixed wings, fixed portions of flapping wings, fuselage structures that could produce significant lift, etc.
  - All wings must have the same flapping rate and roughly the same range of motion.

THE ORNITHOPTER SOCIETY

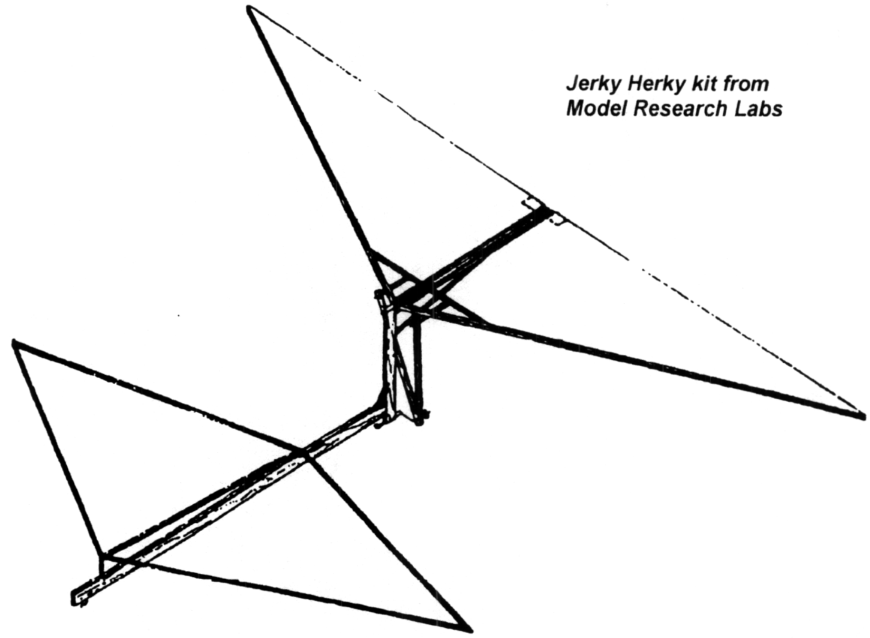
# Jerky Herky Kit Review

*by Sean Frawley*

Recently, Model Research Labs has released a new ornithopter kit. Aimed at beginners, it has followed the tradition of Flapping Flyer and Flutterby by being an indoor ornithopter. Jerky Herky is a canard monoplane with a span of 48 cm (19 inches) and an all up weight of a few grams. The kit is very thorough. It includes enough wire and aluminum to build 3 models and enough balsa and mylar to build 5 or 6. Full-size plans are provided along with a nice sketch of the completed ornithopter. The 11-page instruction booklet provides very detailed directions on how to build the ornithopter plus many tips useful for building any model aircraft. Model Research Labs also offers different sizes of mylar and a wide assortment of aluminum and carbon fiber tubes that are perfect for ornithopters. I recommend you get a catalog from them, as it contains many things useful for ornithopters. Here is the address:

Model Research Labs
25108 Marguerite #160
Mission Viejo CA 92692
www.bestpc.com/mrl

Building the model is very easy. Just follow the directions closely and you'll have a light, strong model. Construction is with the traditional balsa, music wire, and aluminum tube, but it is covered with thin mylar. The structure is one of the simplest I've seen, a basic triangular canard on a solid motor stick with membrane wings. The instruction manual starts out on how to strip the wood and how to make light glue joints. It then goes on through the entire assembly process and even gives a detailed lesson on rubber motors. Building Jerky Herky is a snap. The low part count allows you to get into the air about 3 hours after you open the box. This also makes repairs easy.



*Jerky Herky kit from Model Research Labs*

Although MRL claims Jerky Herky can fly for 90 seconds, the best flights I got from the version on the plan were around 1 minute. Since I had difficulty getting climbing flight, I decided to build three models, each slightly different. The first was rather robust and pitched wildly after launch. A triangular stabilizer was added rear of the flapping wings. Flight became smooth, and times shot up to around 2 minutes. The second version was too light. The motor stick snapped during a flight that probably would have exceeded 1 minute. The final version used medium balsa for the motor stick and light balsa for the rest of the structure. The best flight was 1:02.4, using a 23 cm loop of 3.2 mm rubber with 820 turns.

Overall, I enjoyed the challenge of an indoor ornithopter. The kit was complete and had high quality materials. The only bad point about the kit is that it is not for someone who has no experience in indoor modeling. The key to many of the techniques presented in the manual is simply practice and patience. Take time to read the instructions, and the ornithopter will fly fine. The people at MRL deserve a big thanks for turning out a high quality ornithopter kit for the general modeling public.

## OS CD-ROM Update

There's still a little time to send in your photos, videos, or other information for the upcoming Ornithopter Society CD-ROM. Send all of it to Tony Baker, 2646 E 5 Place, Tulsa OK 74104. Files that aren't ridiculously huge can be E mailed to tonybaker@naturalflight.com.

If you haven't submitted your form to be listed in the OS member directory, please send your contact info to Tony. Otherwise, *no one will know you exist.* Listing is not automatic, because some people don't want to be listed.

**Check out the Forum at the Flapping Flight Web Site!**
**www.catskill.net/evolution/flight**

This lively online discussion group gives you the inside track on progress toward a human-piloted ornithopter. It's also a great way to talk to others about all your crazy flapper ideas!

**Industrial Evolution**
**PO Box 376**
**Arkville NY 12406 USA**

## Ornithopter Society Membership Info

**Join the Ornithopter Society or renew your membership:** Dues are $12 per year in the USA. Dues outside the USA are $17 US per year. Checks are payable to *Industrial Evolution*.

**Get published:** Nathan Chronister, editor of *Flapping Wings*, invites you to send your articles and photos to be published in this newsletter. Send your material to the address above or E mail it to evolution@catskill.net.

www.catskill.net/evolution/flight

***In this issue:***

## *Quetzalcoatlus!*

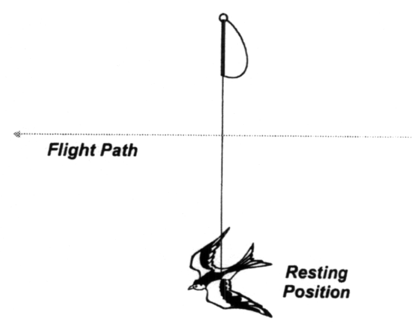
# Safer Test Flights

It's a snowy winter here in New York, the kind we don't get anymore. With over a foot of snow on the ground and no sign it is going to melt, I've been trying to figure out how I can test ornithopters without getting snow all over the tissue paper wings. The solution would also mean safer flight testing in general, a way to keep ornithopters from slamming into the ground during initial tests.

Grant Smith suggested using a long bamboo or other fishing pole with about 7 feet of string to act as a safety while flying the ornithopter in a circle. I'll add that even if the ornithopter doesn't want to fly in a circle, it could be guided in a circle using the string. (PH Spencer used fishing line to steer his free flight ornithopters, but they were flying overhead rather than suspended from a pole.) Using Smith's pole method, it should also be possible to run alongside the ornithopter as it flies. Obviously, if the flight speed is faster than you can run, you'll be limited to a circular path.

I haven't tried the pole method yet, but I did try another technique which permits short test flights indoors. In the system I developed, the ornithopter is suspended from the ceiling so that it cannot touch the floor. It can make short flights before coming to the end of the cord.

For a 60 gram electric ornithopter, I used a length of Edmund Scientific's kevlar line rated at 7 kg. It is about the same weight as sewing thread, so it doesn't have much effect on the ornithopter's flight path. To soften the impact when the ornithopter runs out of string, I used a rubber bungee (2x3x300 mm) tied to the screw eye in the ceiling. In case the rubber breaks or comes untied, the kevlar line is also tied directly to the eye. A snap swivel allows the ornithopter to be removed from the tether quickly and easily. The swivel goes around part of the frame and then clips onto a loop tied in the line just above the swivel. Make sure the attachment point is strong and that the line won't get caught in the gearbox.




This method allows ornithopters to be flown for distances of about 1.5 times the ceiling height indoors with no ground contact. The distance is too short to really evaluate flight characteristics, but it's long enough to spot gross problems. Therefore, I think I'll be testing all of my ornithopters this way, or using Grant's pole method, before I turn them loose on their own.