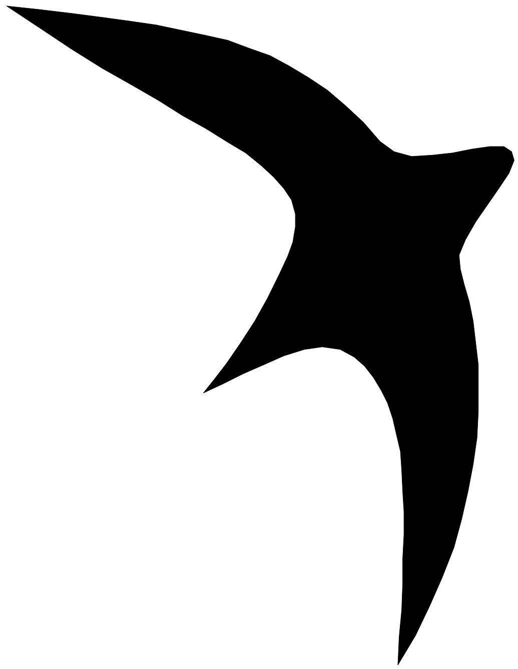

The Ornithopter Design Manual

by Nathan Chronister

The Ornithopter Design Manual

Fifth Edition

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Contents

Ornithopter:

a device intended to fly by flapping wings;

a heavier-than-air flying machine, in which the driving airfoils have an oscillating motion,
in contrast to the rotary motion used in airplanes and helicopters.

I. Introduction

Lie in the grass, and look up, as a delicate, white flying machine circles gracefully in the infinite blue sky. Its tissue wings whisper like leaves as they flap, and the simplicity of its form speaks of the true essence of flight. This is not a real bird, speeding on its way to a meal, nor is it encumbered by the weight of bodily organs. It has no purpose other than flight, no detail that is not expressly devoted to that task. It is the perfect expression of flight, and there are few things more beautiful than an ornithopter in motion.

The term “ornithopter” has been applied to a wide variety of machines, many of which may not appear particularly bird-like. Most make no attempt at the feathered, collapsible wing of a real bird. Some ornithopters have an entirely different configuration such as four wings or a forward stabilizer. They all share the important characteristic that the driving airfoils have a reciprocating motion. In this way, the ornithopter wing is like all animal appendages and unlike the rotating airplane propeller or the wheel of a car.

Flapping-wing devices are extremely varied in form, and the oscillating wing motion is the only thing they all have in common. Beware of supposedly-authoritative dictionary definitions stipulating, for example, that the ornithopter should be “shaped like an aircraft” or derive some arbitrary percentage of its lift from the flapping airfoils. Such definitions have proven themselves unworkable when borderline cases need to be classified. Some people have actually claimed it’s not really an ornithopter unless it has feathers! None of these errant definitions reflect the most common usage of the term.

The ornithopter was conceived as a way for humans to fly. However, most ornithopter experiments are carried out at the scale of a real bird. These little devices draw their inspiration from nature and are not based on a larger manned aircraft design. Therefore it is not appropriate to call them “model ornithopters”. Yet they are models in the sense that they are not real birds. I will use the term “flying bird models” for those ornithopters that are intended to resemble a bird in size and rough appearance. For many, this is more accessible than the word “ornithopter”.

Through our efforts at flapping-wing flight, we are crossing a divide that has traditionally separated machines from nature. Along with researchers in robotics, machine intelligence, and nanotechnology, we are helping technology advance in areas that were formerly the domain of nature, endowing machines with more lifelike qualities.

Why Flapping Wings?

People come to study flapping-wing flight for various reasons. You might be intrigued by the technical challenge; some of us simply need a good problem to solve. Another reason for building ornithopters is that they create such an amazing spectacle. People are blown away when they see one of these machines, flying high overhead, doing something they thought was utterly impossible. Ornithopters are also a great vehicle for education, but the growing interest from universities may have more to do with direct, practical applications for flapping-wing devices.

1. Improved Efficiency. An airplane propeller is only about 70% efficient. Energy is wasted because some of the aerodynamic force produced on the blade acts to resist the motion of the propeller. In an ornithopter, the downstroke blade resistance provides lift, and we can feather the blade during the upstroke so resistance is minimized. Therefore the ornithopter has potentially higher efficiency than an aircraft with a traditional rotating propeller.

2. More Lift. Flapping wings have some additional ways of producing lift and thrust that aren't available with rotating airfoils. One is the clap-fling technique, first discovered in insects. By bringing together the wings and then abruptly flinging them apart, a powerful burst of thrust can be produced. Another technique is delayed stall. Flapping wings don't stall as easily as fixed wings, because the cyclical motion doesn't allow much time for a stall to develop. This allows the wings to produce more lift for a given wing area. But some insects actually do stall their wings, selectively. A stalled downstroke produces a large lift force. These techniques can be used to improve the slow flight and hovering capabilities of the ornithopter.

3. High Maneuverability. The incredible maneuvering of birds is partly due to their small size and partly due to their use of flapping wings. The powered wings can produce larger maneuvering forces, compared with the fixed surfaces on an airplane.

4. Reduced Noise. Airplanes and helicopters make a lot of noise. Much of the noise is produced by the rotating blades and not by the engine. Flapping wings can be nearly silent.

With further development, manned ornithopters could offer the maneuverability of a helicopter, combined with better fuel economy and reduced noise. Although a few technical issues must be resolved, some successful flights have already been made.

Taking advantage of their birdlike appearance, unmanned ornithopters have already been used in wildlife research and to keep flocks of birds away from airports. They can carry spy cameras, in which case looking like a bird or insect helps them evade detection. As capabilities improve, the radio-controlled (RC) ornithopters flown by hobbyists today will pave the way for future autonomous flying machines that can transport goods or perform other tasks. As fossil fuel production continues to decline, present transportation systems will become less cost-effective. Unmanned vehicles might offer a better solution for local transportation of goods. Minimizing the power required for flight will be increasingly important, and this could partially determine whether ornithopters or rotary-driven aircraft are used in various unmanned aircraft roles.

Ornithopter History

Although this is mainly a book about ornithopter design, it is essential for anyone involved in ornithopters to be aware of our historical background. This is certainly valuable for the sake of learning how ornithopters are built. It is also to avoid misinformation, all too common in a field where information itself is hard to find. Journalists, for example, are constantly issuing false headlines about the “world’s first ornithopter”. There is simply a lack of awareness of what has already been accomplished.

Some present-day experimenters might be unhappy to learn that so much has already been done. Perhaps you were hoping to build the “world’s first ornithopter” yourself. But you can take heart in the fact that there is still plenty of new territory to be covered as we farther advance the field. If you have been led to this hobby by a desire to innovate, you will never exhaust the opportunities.

As a builder of ornithopters, you should be aware that the average person doesn’t know the word, has only a vague notion that people have tried to fly by flapping wings, and is completely unaware of the progress that has been made in our field. Moreover, many in the aviation community have a very negative attitude toward flapping wings. I suppose this is rooted in the old newsreel films, in which failed ornithopter attempts were used as a source of amusement, or frequently published rhetoric claiming the impossibility of mechanical flapping-wing flight. These attitudes not only hinder the development of ornithopters, but likely have hindered the propagation of information about past successful flights.

It is true that our field has attracted more than its share of crackpots: people who believe in the flapping-wing approach, but don’t have enough understanding to make a respectable effort. An injustice is done when the media focus on these rather than the credible efforts of the many highly competent individuals working on flapping wing flight. We can see from birds and insects that flapping-wing flight is efficient and practical. Some may believe that mechanical devices cannot achieve the same results, but any such claim is without foundation and easily disproved by example. There is a popular misconception that flapping flight is somehow the exclusive province of living things. We are building ornithopters in part to set the record straight.

Due to the scarcity of information, any history of ornithopters will likely omit some past events. I have been studying ornithopter history for twenty years, and from time to time, I still learn about a major accomplishment that was heretofore unknown to me. Most of what I do know comes from people like you, each of whom shared a little piece of the story. I invite you to do the same.

Often, Leonardo da Vinci is credited with the invention of the ornithopter. However, the idea goes back much farther. The ancient Greek legend of Daedalus and Icarus describes the construction of ornithopters. Some others either proposed, or actually constructed, artificial wings during the intervening years before Leonardo made his famous ornithopter sketches. Now we jump ahead to the first successfully flown flapping-wing devices.

The Early Years

In 1870, Gustav Trouvé demonstrated an ornithopter to the French Academy of Sciences. It flew a distance of 60 meters, powered by a series of twelve gunpowder charges exploding into a bourdon tube. The overall shape was like that of a bird. The wings were undercambered and presumably flexed in a manner similar to the wings of a bird or insect. While the use of explosives to power an ornithopter may seem a bit extreme, it is essential to provide a high power-to-weight ratio when building any ornithopter.

The following year, Jobert produced an ornithopter powered by rubber band. It was a “monoplane” type ornithopter, having two wings like a bird. However, the rubber band was stretched to store energy, not twisted the way it is done today. In 1872, Alphonse Penaud and Hureau de Villeneuve flew other monoplane ornithopters, but they used the modern method of twisting the rubber band. Jobert returned with the first known biplane (four-winged) ornithopter.

So far, the necessary flexing of the wings had been achieved passively, in response to the aerodynamic forces acting on the wings. Around 1874, Victor Tatin developed a more complex flying bird model, in which a mechanism actively drove the twisting of the wings. His design was adapted by Pichancourt, whose Oiseau Mecanique rubber-powered bird was sold in Paris as a divertissement around 1879, the first commercial application for ornithopters.

Lawrence Hargrave of Australia was one of the pioneers who helped amass the information necessary to build the first successful manned airplanes. He did a lot of work with fixed wings, in the form of kites, and he also studied flapping wings. His ornithopters, constructed from 1887 through 1892, were powered by steam, compressed air, and rubber under tension. The rubber pulled a cord that was wound on a flattened spool, which allowed the energy to be used more efficiently. One of the compressed-air-driven ornithopters weighed 2 kilograms and flew more than 100 meters. It is housed at the US National Air and Space Museum in Washington, DC.

Hargrave introduced a simple idea which would become very controversial: He enlarged the horizontal stabilizer. Instead of providing a small amount of lift, as it does in birds, the stabilizer in some of Hargrave’s ornithopters took on a much larger portion of the total weight. The reduced size of the flapping wings resulted in a much greater power output from the ungeared power systems Hargrave was using. Subsequent researchers would follow this example, finding it easier than providing the necessary gear reduction to flap a larger set of wings. Unfortunately, some later enthusiasts got the false impression that the small-flapper designs were more efficient. With proper gearing, this is not the case.

The word “ornithopter” itself dates back to around 1908, according to dictionaries. It is from the French “ornithoptère”, which in turn was derived from the ancient Greek words ornithos (bird) and pteron (wing). It is interesting to note that in his 1894 book summarizing the *Progress in Flying Machines* up to that time, Octave Chanute did not use the word “ornithopter”, referring to them instead as “mechanical birds”.

The Golden Age

In 1929, in Germany, a manned ornithopter designed by Alexander Lippisch flew a distance of about 300 meters after tow launch. This was the first manned ornithopter to achieve any kind of success. The use of a tow launch has caused some to question whether the aircraft was actually flying, which is to say, we don't know for certain if the ornithopter achieved an equilibrium state where the flapping was sufficient to maintain both speed and altitude. In any case, it was powered by the muscular exertion of the pilot, and therefore any flight was bound to be short.

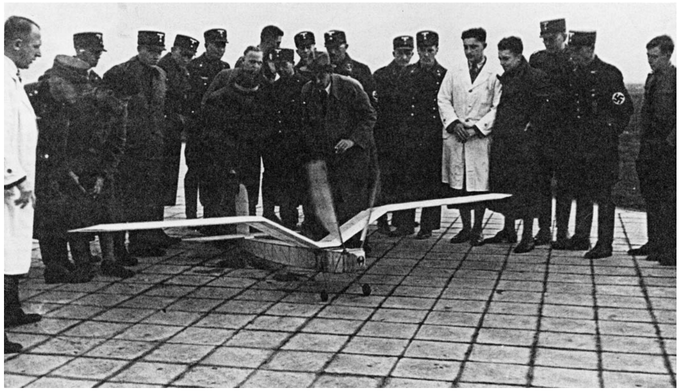
In the 1930s, Lippisch was in charge of a youth organization aimed at recruiting and training would-be pilots. He and his students built a wide variety of unmanned ornithopters, powered by rubber band as well as internal combustion engines. (Although Trouvé's gunpowder motor used a sort of internal combustion, these were the first I know of to use a standard piston engine.) Following the example of Hargrave, these ornithopters had small flapping wings and larger "fixed" wings, but their design benefited greatly from the extensive analytical work carried out by Lippisch and his students. They achieved flight times up to 16 minutes.

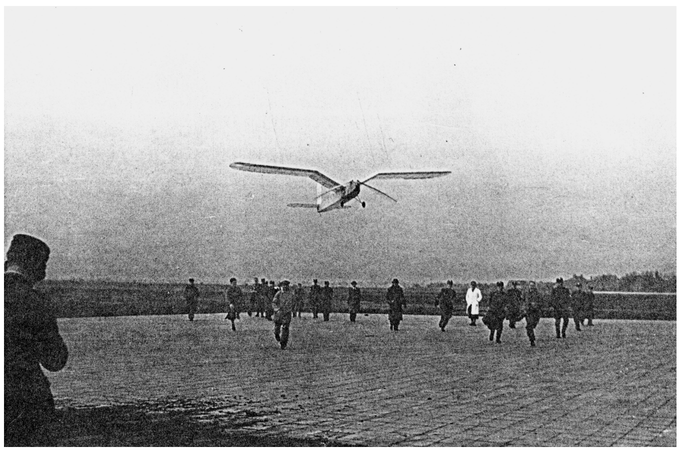
Also in the 1930s, Erich von Holst in Germany developed a series of very lifelike flying bird models, and he also explored four-winged designs based on the dragonfly. All were powered by rubber band, but he used various pulley systems to extract as much energy as possible from the rubber and provide the mechanical advantage necessary for flapping large wings. Flying models were popular in the US during the 1930s. Aeromodelling clubs began to compete with rubber-band-powered ornithopters. The Chicago Aeronuts were at the forefront.

Although Holst's work was significant for present-day ornithopter research, it was Lippisch's small-flapper design that would lead to the first really successful manned ornithopter flights. During World War II, Lippisch himself was engaged in developing the Me-163 Komet rocket-powered fighter plane. Adalbert Schmid meanwhile constructed a manned ornithopter based on the 1930s small-flapper ornithopters developed by Lippisch and colleagues. This machine was originally flown by human muscle power. In June, 1942, outside Munich, it flew a distance of 900 meters, but it still required a tow launch for takeoff. Later, a 2.2 kW motorcycle engine was installed in the aircraft, allowing it to take off unassisted and fly for extended periods.

In 1947, Schimd built a second manned ornithopter. This one was likewise engine-powered, but it was larger than the first. It was based on a Grunau-Baby 2A sailplane, which had been modified so that the outer portions of the wings could flap.

Because of Schimd's old age and the turmoil in his country after the war, the manned ornithopter development was not continued. But in the US, an unrelated series of events would soon lay the groundwork for today's radio-controlled (RC) ornithopter hobby.





Alexander Lippisch led the development of engine-powered ornithopters in the 1930s. Iowa State University Archives.

Percival H. Spencer with one of his "Seagull" ornithopters. Photo courtesy Dale Anderson.

Spencer Seagulls and Orniplane

When he was thirteen, in 1911, Percival H. Spencer made his first flights in a hang glider of his own construction. He later designed the Republic Seabee, a popular amphibious airplane. A toy ornithopter he designed, called the Whamo Bird, was introduced in 1958. Around the same time, Spence (as he is called) was building and flying a whole series of engine-powered ornithopters. They ranged in size from less than a meter wingspan to almost 3 meters. They used model airplane engines ranging from 0.02 to 0.15 cubic inch displacement. Referred to as the “Spencer Seagulls”, these ornithopters had fiberglass bodies and decorated wings, which gave them a realistic appearance.

Spencer collaborated with sailing enthusiast Jack Stephenson to develop the first known radio-controlled ornithopter, the Spencer Orniplane. The Orniplane, flown in 1961, had upper and lower wings flapping in opposition, in order to provide a smoother ride for the vibration-sensitive early radio control equipment. The Orniplane was intended as a proof-of-concept model for a manned ornithopter, which also would have benefited from the opposed flapping, had it been built. The flappers were constructed like boat sails, and their tension could be adjusted as a means of flight control, in addition to the elevator and rudder. The Orniplane took off unassisted.

Recent Progress

In 1984, Patrick Deshaye began publishing a newsletter to help ornithopter enthusiasts around the world to pool their information. The group was called the Ornithopter Modelers’ Society, later renamed the Ornithopter Society. Initially, none of the members knew about Spencer’s work or Schmid’s successful manned ornithopter flights. As previously unknown projects came to light, and as members shared their own plans and ideas, this helped accelerate the development of ornithopters. Some of the members were competing in indoor, rubber-powered ornithopter contests organized by the US Academy of Model Aeronautics. They discovered the highly effective “canard biplane” configuration, and their flight times rocketed from about 5 minutes to Roy White’s current record of 21 minutes, 45 seconds, set in 1995. Other members were interested in developing engine-powered ornithopters. But perhaps the main result of the Ornithopter Society was that it got more people interested in ornithopter research.

In the same year, and unbeknownst to any of us in the West, Valentin Kiselev flew a radio-controlled, biplane ornithopter in Russia. It had thick-air foil wings, in contrast to the membrane type more commonly used. They resembled the wings of an airplane but had to be specially designed to allow the necessary twisting of the structure that would allow each part of the wing to have the correct angle of attack throughout the wing beat cycle. Horst Räbiger of Germany was working along similar lines. In 1990, he flew his EV7 ornithopter, which differed from Kiselev’s in having actively driven wing twist, electric power, and a monoplane configuration. A year later, Jeremy Harris and James DeLaurier flew an engine-powered ornithopter with passive, thick-airfoil wings from a windswept Canadian hillside. This machine was mistakenly hailed by the news media as the “world’s first ornithopter”.

Another noteworthy accomplishment was the 1986 replica of the pterosaur, *Quetzalcoatlus northropi*. The half-size model, nicknamed QN, had a 5.5 meter wingspan and was built by Aerovironment under the leadership of Paul MacCready. Although this aircraft didn't have enough power to maintain altitude, it realized some exciting methods for ornithopter flight control. QN had eighteen servo motors for the fore and aft movement of the wings, head position, claw extension, and other functions, all controlled by an onboard computer. The large head of the pterosaur made it laterally unstable, but this problem was solved by using the head as a forward rudder, actively compensating for the instability. Likewise, fore and aft wing position was adjusted in order to overcome longitudinal stability problems. Although stability was maintained by the on-board computer, the direction of flight was controlled by a pilot on the ground. The gyroscopic stabilization system mimicked the nervous system of flying animals.

In 1997, Sean Kinkade developed a large, radio-controlled ornithopter. It had membrane wings with a flexible brace across the diagonal, loosely based on the Spencer Seagulls. Starting in 1998, this design was marketed as the Skybird. Though in limited quantities, it was the first commercially available RC ornithopter. Some small, electric RC ornithopters soon followed. Kinkade released several of his own, but the Cybird, from Neuros Co. Ltd., of South Korea, saw greater distribution. The Cybird was manufactured in two different versions: the P2, with a 1 meter wingspan, and the P1, introduced later with a 0.75 meter wingspan.

I took over publication of the Ornithopter Society newsletter in 1992. One of my first projects was to introduce a simplified ornithopter design, with the goal of making it easier for newcomers to get started in the hobby of building ornithopters. The original Freebird design has gone through several revisions and spawned some kits, including the Phoenix flying bird model and the Luna, which introduced a simple scissor-like mechanism for flapping four wings. These kits have made it possible for middle and high school students to build their own ornithopters.

Micro Air Vehicles

In 2000, the MicroBat, developed by Aerovironment and Caltech, was the first micro-sized ornithopter resulting from the US government's Micro Air Vehicle (MAV) funding. The MicroBat had three-channel radio control and used the newly available lithium-polymer battery technology. Now, university teams take part in MAV ornithopter competitions. Many of these use the scissor-wing design of the Luna kit, and some toy RC ornithopters have been derived from the MAV ornithopter technology.

MAV applications, such as spying, require the ability to maneuver in tight spaces, in other words, hover. Although some hovering freeflight ornithopters had been built by hobbyists, Mentor, developed at University of Toronto in 2002, was the first hovering ornithopter with radio control. The elements of hovering and small size came together in the Delfly series of ornithopters, developed at the Technical University of Delft and Wageningen University in 2006. These ornithopters are able to transition between hovering and forward flight. They also carry a small video camera. The live images are analyzed by a computer on the ground, giving Delfly the capacity for autonomous navigation.

Types of Ornithopter

Flapping-wing aircraft are even more diverse in form and body plan than the flying creatures they imitate. As you can tell from the above historical information, ornithopters vary quite a bit in size. The lightest weigh less than a gram and are powered by thin rubber bands. The rubber band is wound up with a twisting motion, in some cases more than a thousand turns, often using a special winding device. The most delicate models are flown indoors, and the flight duration is limited by the height of the ceiling. Thus, indoor competitions are held in large buildings such as domed stadiums or hangars.

Larger, heavier ornithopters are usually powered by an electric motor, or in some cases, by an internal combustion engine. Electric-powered ornithopters usually weigh from several grams up to a few kilograms. For anything bigger than that, such as manned ornithopters, it might make sense to use an internal-combustion engine. The internal combustion engine is more difficult to mount, further complicates the design through its cooling and starting requirements, and is more difficult and messier to operate. The cost of rechargeable batteries increases with the size of the ornithopter, and at some point this might outweigh the advantages of electric power.

The level of difficulty also varies with the type of model. The lightest rubber-powered ornithopters are extremely challenging to build. However, those designed for beginners are quite easy. Thanks to the small motors and gears now available from Didel, Switzerland, it has gotten much easier to design and build small electric ornithopters weighing 10 grams or so. Improved battery technology, and the opportunity to borrow ideas from proven designs, will also help you with larger electric ornithopters, even though these tend to be much more complex. If you are going to build any kind of electric-powered ornithopter, you should start with some rubber-powered ones first, to acquire the knowledge and skills you will need.

Aside from the different power sources, there is a great variety of different wing configurations, each with its own special characteristics.

Monoplanes

The monoplane ornithopter has a left and right wing: two altogether, even though monoplane literally means “one plane”. Even the individual ornithopter wing is not planar, because the angle of the wing varies along the span. We are using the terminology that was developed for airplanes, even though it doesn’t quite fit here. The monoplane configuration is simple to construct, fairly efficient, and well-suited to rapid forward flight.

Biplanes

A biplane ornithopter has four wings, forming an upper pair and a lower pair. Usually, there is no vertical gap between the upper and lower wings where they meet the fuselage. The upper and lower wings clap together, aiding in propulsion. Also, you get twice as much wing area in the same size ornithopter. (This is useful for MAV competitions where the overall size is limited.) For these reasons, biplanes usually have a substantial performance advantage over monoplanes. They are capable of much slower flight and are much more likely to be able to hover. Seeing these advantages, some ornithopter enthusiasts have embraced the four-winged insects, rather than the birds and bats, as a model for ornithopter design. Biplanes are, unfortunately, more complex than monoplanes to design and build.

You might expect that a biplane ornithopter would require a thicker rubber band, or more gear reduction, to flap the extra wings. You might also expect that it wouldn't need to flap as fast as a monoplane, because of the extra wing area. Both assumptions are incorrect. If the total flapping arc is the same, each individual wing would only have half as far to travel, greatly reducing the torque requirement. The shallow flapping also means that a comparably high flapping rate must be maintained, despite the generally lower power requirement.

Tandems

A tandem ornithopter also has four wings. Instead of upper and lower wing pairs, the tandem has its wings arranged in a front pair and a back pair. Tandem ornithopters have been popular because of their similarity to dragonflies, and because they are potentially easy to build.

It can be quite difficult to transfer power to the rear pair of wings, but tandem ornithopters usually avoid this complexity by using a rocking motion of the fuselage to transfer power. In these "reaction tandem" designs, the front wing spar is a single piece, which supports the left and right front wings. This front wing spar is driven in a seesaw fashion: one side goes up as the other side goes down. The reaction force causes the body of the ornithopter to roll back and forth, which in turn flaps the back wings, because they are rigidly attached to the fuselage.

Reaction tandem models usually have a generous spacing between the front and rear wings. As long as the front wings have a slight positive incidence relative to the back wings, no horizontal stabilizer is required. If the wings are actively driven, the front and rear pairs tend to be closer together, and a stabilizer is often used.

Performance of tandem ornithopters may seem inconsistent. The rear wing operates in the wake or vortices created by the front wing. The forward speed, and the relative timing of front and rear wings, as well as the amount of space between them, will determine how the rear wing interacts with those vortices, greatly affecting performance. For models with closely spaced front and rear wings, performance is typically best if the rear wings lead the front wings by about a quarter cycle.

Forward Stabilizer

The typical airplane has a large pair of wings in front and a small wing in back called the horizontal stabilizer. However, the relative sizes of the front and back wings may vary. In the tandem aircraft, the front and back wings are about equal in size. If the front wings are smaller than the back wings, this wing configuration is referred to as a "canard". I hesitate to use this name, because canard is French for duck, and ducks don't have a forward stabilizer. Many ornithopters do, however.

The technique is particularly useful in rubber-powered ornithopters. When seeking to maximize the flight time, one approach is to increase the length of the rubber band and motor stick. The long fuselage inevitably extends far from the center of lift of the main wing, so the fixed stabilizer ends up supporting much of the weight. The forward location of the stabilizer keeps it out of the turbulent wake of the flapping wings, improving its lift-to-drag ratio.

Tailless Ornithopters

With ornithopters, it is difficult to achieve longitudinal stability without some kind of horizontal stabilizer. Many ornithopters have a reduced stabilizer in order to more closely resemble an insect, bat, or pterosaur. Completely tailless ornithopters are rare, and there is no set formula for making them work.

Fixed-Lift Ornithopters

To varying degrees, most ornithopters derive some lift from non-flapping surfaces such as the stabilizer, fuselage, and any additional fixed wings. Birds likewise use the body and tail as lifting surfaces. Since the amount of lift from fixed surfaces varies along a continuum, it is not possible to strictly categorize various ornithopters as either "fixed-lift" or "flapper-lift". Efforts to do so, for the purpose of drafting contest rules, have met with frustration.

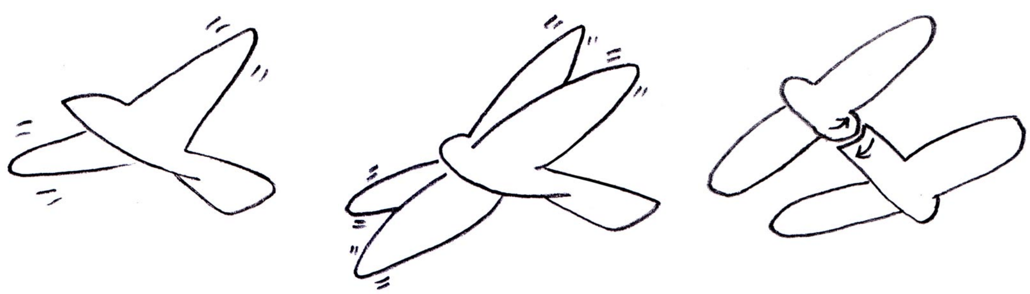
In some cases, the fixed lifting surfaces are blatant, but I don't think there is any advantage to this configuration, other than the fact that you won't need as much gear reduction, or in the case of rubber power, you won't need as thick a rubber band, to flap the smaller flapping portion of the wings. An equivalent alternative is to flap the entire wing area, but move it through a shorter arc.

The fixed wing does not offer a free ride. It is merely a device for converting forward thrust, which acts over a great distance, into a vertical lifting force that acts over a shorter distance. Extra thrust is needed to overcome the induced drag of the fixed wing. The power requirement is about the same, either way.

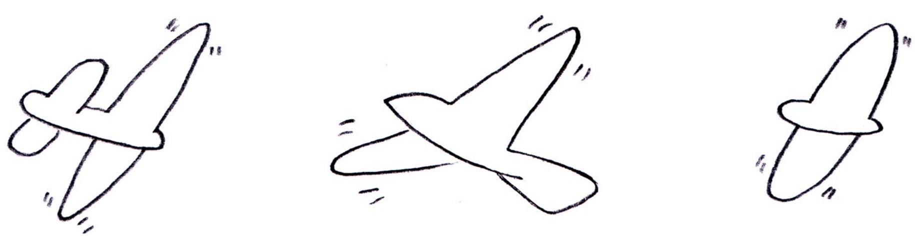
Even within the flapping wing, there are separate regions for producing lift and thrust. The outer part of the wing produces most of the thrust, due to its greater vertical flapping motion. The inner part, near the body, has less vertical motion and produces lift due to the ornithopter's forward motion through the air. Most ornithopters, like most airplanes, rely on their forward motion, and not the flapping of the wings per se, to produce lift.

You can't judge the share of lift by the relative area of surfaces. Typically, the relative load on the front and back wings is determined by the location of the center of gravity, relative to the centers of lift of the front and rear wings. If a third pair of wings is added in the middle, then its lift share will be determined by angles of incidence. The same is true for flapping outer portions of a wing. Even if the flappers are quite small, they will be the sole source of lift when the ornithopter is hovering.

It should also be noted that any "fixed" wings will actually move up and down considerably, in reaction to the flapping, just as the whole ornithopter body rises and falls. Even with completely rigid wings, this motion may enhance the lift-to-drag ratio and even allow some thrust to be produced. As with the reaction tandem ornithopters described previously, body motion can be used deliberately to drive wings.



Some common ornithopter types are the monoplane (two wings), biplane (four wings in upper and lower pairs), and tandem (four wings in front and rear pairs). This picture shows the counter-flapping mechanism of the reaction tandem ornithopter.



The fixed (non-flapping) stabilizer may be in front, in back, or absent.

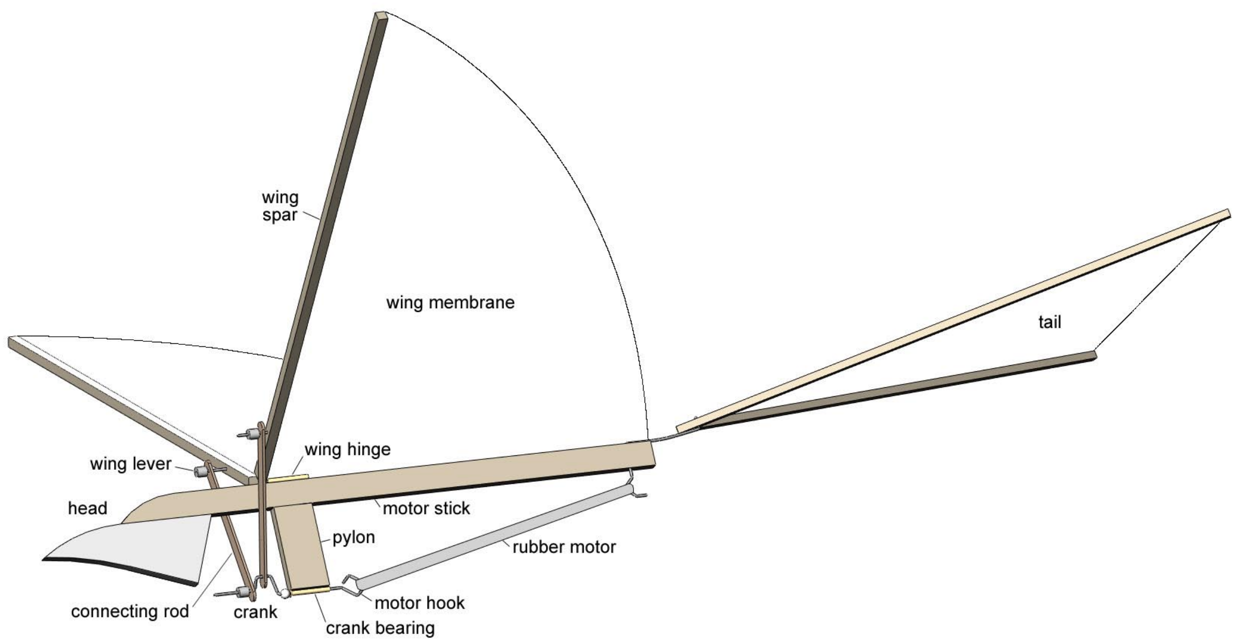
II. Your First Ornithopter

In any field of study, it is wise to start out with simple projects, suitable for the beginner. This is especially true for ornithopters, since they are so difficult to design and build successfully. There is a logical progression from introductory to more advanced projects as you take on more of the design and engineering yourself. Even if your sole purpose in reading this manual is to learn to design and build a radio-controlled ornithopter, the best way to learn is by building a simpler, rubber-powered model first. This will save you a lot of frustration and make your first experience with ornithopters much more enjoyable. You will have plenty of opportunity to try your own ideas later on.

Parts of a Typical Ornithopter

Before we get into a lot of specifics, here is a quick overview of typical ornithopter construction. I've chosen a rubber-powered ornithopter for this example. Many of the parts will be the same for electric-powered ornithopters as well. Although there is quite a diversity of ornithopter types, most of them can be described using similar terminology. Most use a similar flapping mechanism and have many of the same parts.

You will notice that the typical ornithopter has no landing gear. They are launched by hand or by sliding along a smooth floor. They land on their bellies, in a manner somewhat less graceful than real birds. A few ornithopters have been equipped with wheels, but since the aim is usually to make the ornithopter look something like a bird, this is not very common.



Parts of a typical ornithopter are shown on the Ornithopter Zone's Phoenix model kit.

Building From a Kit or Plans

The easiest way to get started is to build a rubber-band-powered ornithopter from a kit. You should choose a kit that was specifically designed for beginners. The Ornithopter Zone's Falcon kit is the easiest one available, and that will maximize your chances of success. Then you can move on to a slightly more involved kit such as the Phoenix, which allows you to really build your own ornithopter from basic materials like balsa wood and tissue paper.

Even if you have a lot of prior experience building model airplanes, you should probably start with something fairly simple. It is necessary to make some allowance for the fact that ornithopters by nature present more of a challenge, and have certain features that no amount of airplane experience would prepare you for. Therefore, starting with an RC or competition free-flight ornithopter is not recommended, regardless of your modeling skill level.

Even though I wouldn't recommend it, some people will insist upon building their first ornithopter without a kit. For that reason, I've included a beginner ornithopter plan in this manual. The original Freebird appeared in the Flapping Wings newsletter in 1993. Over the years, I've improved and simplified the design. This latest version should be fun and easy to build, for anyone who has some prior experience building balsa-and-tissue model airplanes.

Freebird was the basis for the Phoenix kit, and they are very similar. However, the kit form is much easier to build because of the pre-drilled connecting rods and other specialized parts that simplify the construction. To build the Freebird, you will need to make a strong wood-to-metal bond, using epoxy or CA glue. For the kits, however, all you need is white glue, which is non-toxic and less expensive. Unless you already have some of the required materials, you will find that the kit is much cheaper than buying all the materials separately.

The Freebird or Phoenix should fly quite well despite its beginner-friendly, rugged construction. If you lubricate the rubber band, you can put up to about 220 turns on it, and that should give you flights up to one minute. The actual flight time can vary, depending on such things as the density of the balsa wood. It is interesting to note that the density of balsa wood can vary by a factor of three or more, affecting its weight, stiffness, and strength.

However, if your Freebird or Phoenix won't fly for at least 30 seconds, something is definitely wrong. This could be due to a poorly built flapping mechanism, incorrectly applied wing tissue, or incorrect flight adjustments. If you built the Freebird from plans, often the problem is with the crank bearing. The hand-cut tubing may be uneven, preventing the crank from turning freely when the rubber band is pulling it back against the front of the tube. A poorly made crank bearing can altogether prevent your ornithopter from flying. This problem is avoided in the kit, with its pre-formed bearing.

When building from plans, it is essential to follow the instructions. Don't use a paper clip instead of music wire, and don't substitute ordinary rubber bands for model airplane rubber. Things like this can determine your success or failure. Once you've completed the Freebird, you'll find more plans on the Ornithopter Zone web site, and in the ornithopter newsletter, *Flapping Wings*.

Whether you are building from plans or designing your own machines, you will need a source of parts for your ornithopters. Your local hobby shop probably has all of the necessary supplies for the Freebird. More advanced rubber-powered models may require special indoor modeling supplies. Get a book on indoor model airplane construction if you plan to build any of the lightweight, indoor ornithopters. If you choose to build larger, electric-powered ornithopters, you will probably find the usual radio control suppliers very helpful. You will also need a source for gears, shafts, bearings, and other mechanical parts. I highly recommend purchasing these items, rather than trying to scavenge parts from old clocks and VCRs. Some sources are listed in the back of the book.

Some people will get started by purchasing a ready-made toy ornithopter. There are several different products on the market now, including rubber-powered freeflight and electric RC ornithopters. Some of these have detachable wings, so you can replace them with your own new wing design for experimentation. In the case of the classic Tim Bird toy from France, it is possible to triple the flight duration through various modifications. The plastic body is quite durable and will survive many experiments.

Simple Experiments

Once you've built the Freebird or Phoenix, I would like you to try some simple experiments with your ornithopter. These experiments will help you understand some important concepts that will be useful later on.

Asymmetric Flapping

First, let's study the effect of asymmetric flapping of the wings. The required modification is very simple. All you have to do is reposition one of the connecting rods so they are both sharing the same part of the crank arm. When you turn the crank by hand, you will observe that one wing begins each downstroke and each upstroke slightly before the other wing. We say that the wings are slightly "out-of-phase". In this case, one wing is leading the other by about 30 degrees of crank rotation. What effect will this have on the flight? First, try to guess what will happen. Then, fly the model and see if your understanding is correct.

Next, we will try an even more extreme example of asymmetric flapping. For this experiment, we will reposition the connecting rod for the left wing so that it is all the way back against the plastic bead that serves as a crank bearing. This reduces the flapping amplitude to zero degrees, basically locking the wing in place. The other wing is still free to flap with the normal range of motion. What do you think will happen now?

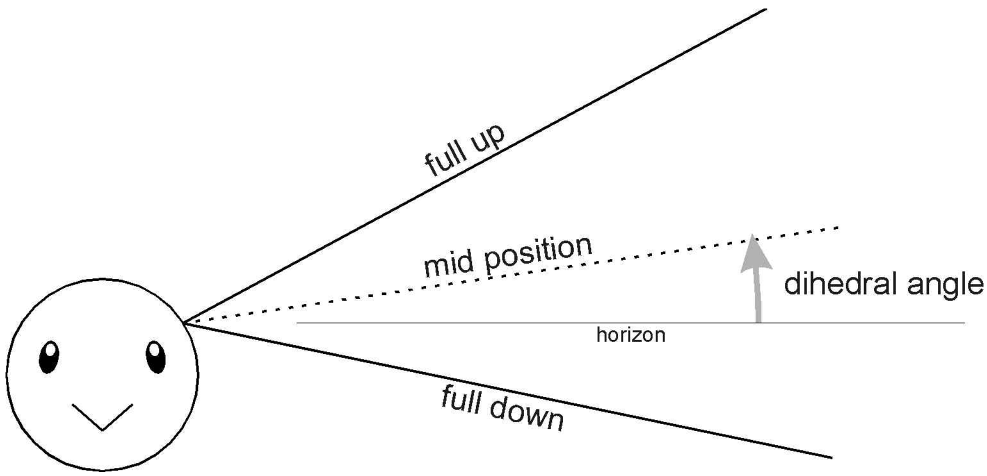
Obviously, the ornithopter now flies in a circle. It circles to the left, toward the un-powered wing. The circle might be so tight that your model dives into the ground. How does this compare with the previous modification? You might be surprised to find that the amount of turning is similar, despite the seemingly drastic step of locking one wing in place.

Notice that when the model is flying, it looks like both wings are flapping. The flapping wing causes a reaction torque on the body, and since the other wing is fixed with respect to the body, it receives a flapping motion due to the reaction torque. Therefore, both wings will appear to flap with an angle of about thirty degrees. The rotational inertia of the body does retard the left wing slightly, and that is what causes the turn. But if you add a little bit of weight to the tip of the right wing, you should find that the ornithopter can be made to fly more or less straight.

Length of Connecting Rods

Here is another simple modification that will tell you a lot about how these machines operate. In this experiment, we will vary the length of the connecting rods, to see how this affects the flight of the ornithopter. You can drill new holes to change the effective length of the connecting rods. Changing the length of the connecting rods moves the whole flapping arc and the midpoint wing position higher or lower.

In airplanes, the wings are often raised slightly above horizontal. The angle between the wings and the horizon is called the "dihedral angle". Dihedral improves stability by keeping the wings level. If the airplane starts to roll to one side, one wing will produce more lift than the other, and that causes the airplane to return to level.



The same principle applies to ornithopters. If the average or midpoint wing position is slightly above horizontal, this results in a "dihedral effect" which helps keep the ornithopter from rolling to the left or right.

Raising the flapping arc has another effect on the ornithopter. Since the wings produce thrust, the effective line of thrust is raised as you raise the flapping arc. Therefore, as you lengthen the connecting rods, the ornithopter will tend to nose-dive. You may compensate for this by bending the tail up a little more, or by adding some weight at the back of the motor stick.

Conversely, if you lower the flapping arc, the ornithopter will tend to stall, or it might begin to roll, which results in a sharp turn and dive. The ornithopter may even try to fly upside down.

Vary the Crank Radius

The crank radius determines the flapping amplitude of the wings. We will compare the standard 3/8 inch crank radius to a smaller, 3/16 inch radius. The large crank provides a flapping angle of about 60 degrees. The small crank will provide a flapping angle about half as great, or 30 degrees. The first step is to collect some data with the standard crank. Then we will perform the modification.

Flight tests should be conducted in totally calm conditions, or in a large indoor space. Starting with a fresh, lubricated rubber band, wind it exactly 150 turns. Use a light, consistent launch technique, and time the flight to the nearest second. It's best to have a friend time the flights using a stopwatch. Record several flight times in a notebook. Ignore any flights that result in collisions with obstacles.

You should also try some different thicknesses of rubber band. For example, in addition to the 1/8 inch rubber, time some flights with 3/16 and 3/32 inch rubber. For consistency, wind each motor to the same percentage of breaking, using the table provided below.

Now we will make the crank smaller. The only way to do this is by making a new crank. Use cutting pliers to remove the old one. When making the smaller crank, be sure to maintain the correct proportions so the flapping remains symmetrical. Start again with a fresh rubber band. Make any necessary trim adjustments. Then record flight times, as with the larger crank.

You probably found that the wings flapped much more slowly with the large crank. With the same number of turns in the rubber band, this should give you a longer flight time. However, the slower unwinding of the rubber band also means a decrease in power output. The model might not climb as well, and the point where the rubber band no longer has enough torque to flap the wings would be reached sooner.

With the small crank, the rubber band has more mechanical advantage to flap the wings. For a given level of torque in the rubber band, the torque available at the wings is much greater. This results in a much higher flapping rate and greater power output. On the surface, it might appear that the shallow wing flapping is advantageous. However, the rubber band will run out more quickly, perhaps resulting in a shorter flight. If you use a thinner rubber band, you can put more turns on it, and that might compensate for the faster unwinding. You should also be aware that if the flapping arc is too shallow, the wings will not produce thrust efficiently.

Once you've studied your flight times, you should have a good sense of how the crank size and rubber thickness affect flight performance. If you graph your data, you can probably estimate the optimal crank size and rubber thickness to get the best performance from your ornithopter. The optimal values will depend on the particular model.

Size (inches)	Turns at Breaking Point	80% Turns
0.030	178	142
0.040	165	132
0.050	158	126
0.062	150	120
0.080	138	110
0.090	132	106
0.100	126	101
0.110	110	88
0.125	97	78
0.188	83	66
0.250	69	55

Maximum turns per inch loop of rubber. Multiply by rubber band length for actual turns. Wind to 80% turns to reduce risk of breakage. Assumes contest grade rubber with lubrication.

Size of Wings

Obviously related to the rubber band torque and flapping angle is the size of the wings. Bigger wings might require a thicker rubber band or smaller flapping angle. First, remove the original wings from your ornithopter. The tissue will be ruined, but you can save the spars for later use. Moisten the wing spars (except for the area around the wing lever wires) and then scrape off the remaining tissue and glue residue with your fingernail. Be careful not to damage the wood.

Next, make a new set of wings with a spar length of 15 inches instead of eight. Do a series of timed flights, decreasing the wingspan two inches at a time, until the model won't fly. You can probably guess what will happen. The flapping rate becomes progressively higher, but at some point the model becomes so inefficient that it will no longer fly, even with the increased amount of power. It would be interesting to explore the effects of rubber size and crank radius with various wing sizes. This process would help you optimize your birds for competition.

Instead of increasing the wing area, you can achieve similar results by reducing the weight. A great starting point would be to construct your own lighter version of the Freebird. The original Freebird was designed to be easy to build, and weight was not the primary concern. There are several things you can do to reduce the weight, such as tapering the wing and tail spars, replacing some of the wire parts with lighter construction, using less wood overall, and using thinner tissue. The lighter construction will allow you to use a thinner rubber band, so the model won't need to be as strong as the original.

It is generally thought that a lighter wing loading (less weight in relation to wing area) results in a lower power requirement and better flight times. However, if you reduce the weight too much, the wings might become overly flexible, resulting in poor efficiency. This is a factor in the preceding wing size experiments. If you could hold the wing flexibility constant, you would see a higher optimum wing size.

III. Design and Construction

Even while you were getting a feel for building a simple ornithopter, and even before you found out about this book, you might already have started to think about how to build a more advanced ornithopter of your own design. That might mean trying to achieve the longest possible flight times with a rubber powered ornithopter, or it might mean moving in the direction of electric power and radio control. Either way, you will find plenty of engaging challenges.

There is really no end to what you can do. Some people want to build ornithopters bigger, and other people want to build them as small as possible. In addition, you might want to try some different, experimental wing designs. I imagine some readers will be developing ornithopters for a specific purpose, such as carrying spy cameras, or to market as a toy. Whatever your particular aims, this next section lays out the important considerations you will need to know about, in order to design your own ornithopter successfully.

Strength and Weight

As one might expect, weight reduction is extremely important in ornithopters. This is true, in part, because ornithopters are mechanically complex. The weight of the flapping mechanism is a necessary burden that airplanes don't have to contend with. At the same time, most ornithopters don't live up to the potential efficiency demonstrated by real birds, so the weight must be less than that of a bird or airplane to achieve comparable performance. The effect of weight is dramatic.

Strength of construction is also important. Ornithopters are subject to greater stresses than airplanes. Loads may reverse in direction and vary in magnitude throughout the flapping cycle. Rubber-powered ornithopters may experience "shock loads" at the end of each wing stroke. At that point in time, there is no resistance or load on the rubber band, so it jumps forward, releasing a large amount of energy that must be absorbed by the structure. For all these reasons, sturdy construction is required throughout. The flapping mechanism, the wings, and the struts that join the wing to the fuselage must be especially strong and securely attached. The required strength must be achieved while keeping the structure very light.

When testing new designs, the ornithopter may be subjected to additional impact stresses, beyond what would be encountered by a proven aircraft. It's best to design your ornithopter so that it can survive a crash. With very small and light ornithopters, this is easily achieved. For heavier models, you'll need to build some flexibility into the structure so it can flex instead of breaking. For example, you might use a fiberglass or plywood plate for the body, instead of an open-frame balsa wood structure. Carbon fiber rods make a flexible wing spar that resists breaking. Glue joints tend to fail in an impact, so reinforcing them (or perhaps using screws instead) is an important part of crash-proofing your bird. A foam head will offer a lot of protection from impacts, as well as a more realistic appearance.

I used to fly ornithopters on a tether so they could be safely tested with no risk of hitting the ground. The main part of this system was a long, horizontal cord, raised about 2 meters off the ground. A thinner cord about a meter long was attached to the first using a plastic ring. The ornithopter was suspended from the other end of the thinner cord. This allowed the ornithopter to travel forward but prevented it from reaching the ground if anything went wrong. Although the system worked well, I really needed a longer run to determine flight performance. Once I learned how to build a more crash-resistant structure, I stopped using the tether system.

Power Systems

Choosing the right motor and battery are both essential for building a successful ornithopter. Here, I will explain some of the different options and how to choose the right power system. I'll also explain some important techniques for getting the most power and efficiency from your chosen system.

How much power is needed, exactly? For typical membrane-winged ornithopters, about 100 watts per kilogram coming out of the motor should be enough power to give your ornithopter a good rate of climb. As ornithopter wing designs approach the efficiency of real birds, it should be possible to get by on somewhat less. Estimates of the mechanical power required for bird flight vary over the range of about 10 to 50 watts per kilogram.

Rubber Band Power

The simplest ornithopters are powered by rubber band. The rubber band combines the functions of motor and battery into one super-convenient package. The rubber band can produce a large amount of torque, so you don't need any gear reduction to flap the wings of your ornithopter. For these reasons, rubber-powered ornithopters are by far the easiest to design and build.

The energy is stored by winding the rubber band with a twisting motion. This causes the rubber to elongate in a helical path. The result is just like stretching the rubber band, except it takes up less space. The rubber band should be lubricated, because the twisting motion causes a lot of rubbing. The grade of rubber is very important. Contest rubber intended specifically for flying models will store several times more energy than standard, office-grade rubber bands. Impressive flight times can be achieved in lightweight models.

The rubber band exerts a certain amount of torque, which diminishes gradually as the rubber band unwinds. The amount of resistance (for example, the size of the wings) affects the speed of unwinding, but not the torque exerted by the rubber band. This is different from other power sources, in which the torque diminishes substantially with increasing speed of the motor.

One reason for the success of rubber-powered models is that the power-to-weight ratio can be increased to any desired level, simply by using a shorter, thicker motor. The thicker motor has more torque and unwinds faster, and both of these factors increase its power output. (This obviously results in a shorter flight.) Although other power sources are less adaptable, rubber can’t store as much energy, per unit weight, as a battery or chemical fuel.

Electric Motors

Most radio-controlled ornithopters are powered by an electric motor and battery. There are several types of electric motor that may be used in an ornithopter. The selection of motor type will depend on your specific project.

The brushed DC motor is the oldest type and the most familiar to most people. These motors have some coils of wire attached to a central, rotating shaft. The coils of wire serve as electromagnets. The motor also has some permanent magnets in the motor casing. The force exerted between the electromagnets and the permanent magnets causes the motor shaft to rotate. Electrically conductive "brushes" transfer electric current to the rotating shaft or armature. The electrical contacts are designed so that as the motor rotates, the various coils or windings are switched on and off in a specific sequence, which allows continuous rotation.

Brushed motors are the least expensive type, and a properly selected brushed motor will supply enough power for most ornithopter needs. The down side is that the brushes cause friction and electrical resistance. That reduces the efficiency of the motor and causes heat to build up. Brushed motors should be “broken in” by running at half throttle with no load, for about an hour. This causes the brushes to wear to a curved shape that provides better contact with the commutator. If you run the motor without breaking it in, the higher current will cause arcing (sparks), which causes pits in the contact surfaces. A small device called an electronic speed control (ESC) allows your radio receiver to control the voltage supplied to the motor.

Most brushed motors have an iron core inside the electromagnetic coils. The iron core provides structure for the windings, helps intensify the magnetic field, and acts as a heat sink if the motor is momentarily overloaded. Some of the smaller motors have a coreless design instead. The coils of wire are bound by a plastic resin. These motors are lightweight and efficient, but they are easily damaged by overheating. The tiny "pager" motors, so named because they allow pagers and cell phones to vibrate, are of this type. These inexpensive motors are the ideal choice for indoor or micro-sized ornithopters.

In a "brushless" type motor, the electromagnets are switched on and off electronically, so there are no mechanical contacts. This is more efficient, and it allows the motor to run cooler. Because these motors require a special type of electronic device called a brushless motor controller, they are relatively new to the hobby industry, and they cost more than brushed motors.

Brushless motors come in two varieties: inrunners and outrunners. The inrunners are the simplest type to understand. In these motors, the electromagnets are around the outside of the motor. The permanent magnet is on the rotating shaft, inside the motor. The electromagnets are switched on and off in sequence, causing the permanent magnet to rotate.

Outrunner brushless motors work on the same principle as inrunners, but they are inside-out. The electromagnets are at the center of the motor, around the motor shaft but not attached to it. Instead, they are secured to the non-rotating face plate. The permanent magnets are on the outside, attached to the motor case. The case rotates and is attached to the output shaft.

Inrunners tend to operate at a higher speed and lower torque compared with outrunners. For that reason, outrunners don't need as much gear reduction. This will usually make the outrunner a better choice for most ornithopters. Less gear reduction is likely to mean less friction and less weight. However, the inrunner might be advantageous if you have an existing ornithopter that's geared for a high-RPM brushed motor. In this case, the inrunner brushless motor would give you improved efficiency compared with the brushed motor, and you might not need to change the gear ratio substantially.

Whatever type of motor you use, there are several factors that influence the power output of the motor. One is the electrical resistance of the motor coils or windings. If the coil has more turns and thinner wire, it will have more resistance, and that means less current will flow at a given voltage. A motor with fewer turns or less resistance is generally more powerful. This can only go so far, however. If you attempt to drive too much current through too small a motor, it will overheat. The coil resistance increases if the motor gets hot. Therefore, the motor speed and power output may decrease during a flight, even if the battery is able to supply a constant voltage. Excessive heating can demagnetize the magnets, permanently reducing the motor's power output. In an extreme case, the windings can even burn up, and then the motor will stop working entirely.

The amount of current flowing through the motor is not only determined by the electrical resistance of the coils. It is also determined by impedence: When the motor is rotating, the shifting magnetic fields tend to impede the flow of current through the electromagnetic coils. If you hold the motor shaft so it cannot rotate, the motor will draw a lot of current and possibly overheat, whereas if there is no load on the motor, it will spin rapidly and draw far less current.

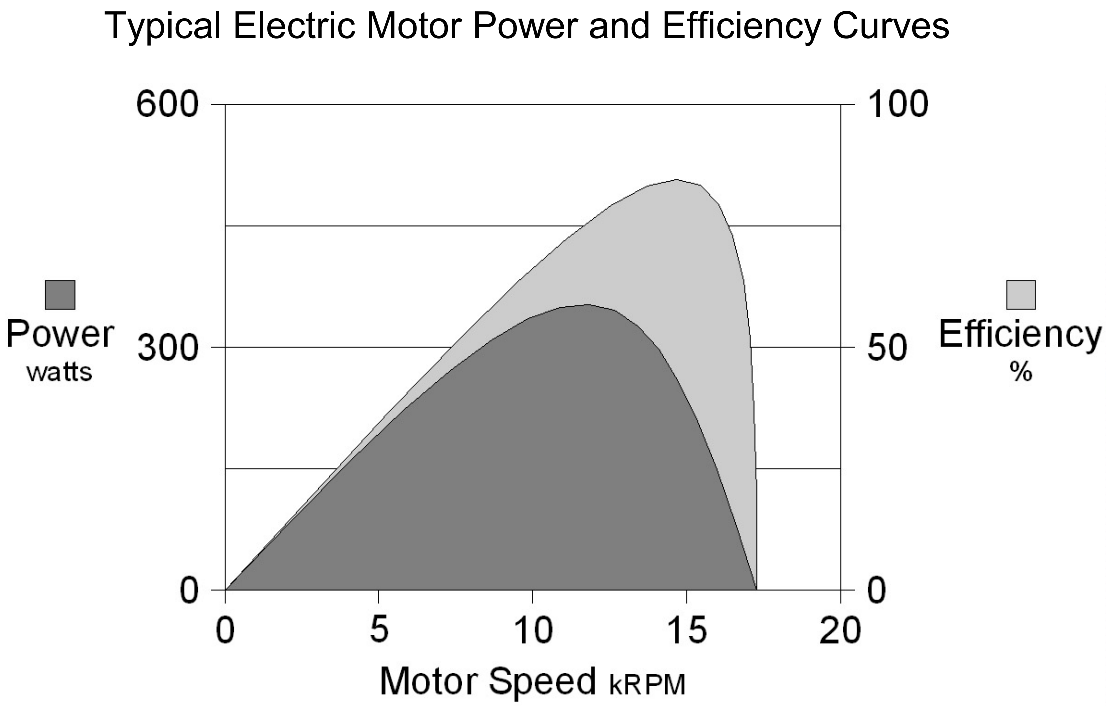
Efficiency is defined as the ratio of power output (speed times torque) to power input (voltage times current). Since the power output is always lower than the power input, efficiency is always less than 100 percent. The remaining energy goes to heating the motor. For this reason, a more efficient motor will tend to run cooler, and it can be made smaller since the size of a motor partially determines how fast it can dissipate heat.

Motor’s Input Power (measured in watts) = amps * volts

Motor's Output Power (measured in watts) = torque * rotational speed
= torque(in newton-meters) * RPM * 2π / 60

Motor Efficiency = output power / input power

Brushless motors can achieve efficiencies as high as 80%. However, the actual efficiency depends on the loading of the motor. Obviously, if the motor is stalled (no rotation) the efficiency is zero, because the motor is drawing a lot of current and not moving. There is input power but no output power. Likewise, if there is no load on the motor, it is not doing any work because there is no torque being exerted by the motor shaft. The optimal efficiency lies somewhere in between, and usually around 80% of the no-load RPM. With ornithopters, we strive toward the maximum efficiency speed by adjusting the gear ratio, the size of the wings, or the flapping amplitude.



There is also a particular speed where the motor achieves its maximum power output. The maximum power speed is lower than the maximum efficiency speed, typically about half or two-thirds of the no-load speed. If you are able to run the motor at its maximum power speed, that should give the best climb in a short burst. In many cases, though, the motor will overheat if you try to run it at the maximum power speed for any length of time. For that reason, it may be better to reduce the load (by making the wings smaller, for example) and run the motor at a higher speed where it will draw less current. This will also give you more efficiency and a longer run.

Batteries

The other half of the power system is the battery. The motor and battery together determine the power output of your system. For example, if you need 100 watts to fly your ornithopter, then the motor and the battery each must be able to provide 100 watts. When writing about motors above, I kept things simple by assuming that the battery would be able to maintain the same voltage no matter how much current the motor was drawing from it. In reality, the battery voltage drops as you draw more current. It's important to know how much current the battery can supply without substantially lowering its voltage. As with motors, if you draw too much current, it can cause permanent damage to the battery.

The battery discharge rating tells you how much current you can safely draw from the battery. The discharge rating might be given in amps, but more often the discharge rate (amps) is divided by the capacity (amp-hours) to give a rating that is independent of the size of the battery. For example, a rating of 10C indicates that the battery can be discharged at a rate of 10 times the capacity per hour. (In other words, you could fully discharge the battery in one tenth of an hour.) You multiply the capacity by the rating to get the actual rate of current flow. For example, if the battery has a capacity of 800 mAh, you multiply 0.8 Ah by 10 /h and the result is 8.0 amps.

Meanwhile, the battery capacity will determine how long you can fly. If the motor draws 4.0 amps and the battery has a capacity of 800 mAh, then the motor will run for 0.8 Ah divided by 4.0 amps, or 0.2 hours. That's equal to 12 minutes.

There are several types of battery on the market. None of them are very good, compared with the fat birds use to store energy. The amount of energy stored in fat is about 10 watt-hours per gram. Can you imagine a 1 gram battery putting out ten watts of power for a whole hour? Probably not, because the best batteries on the hobby market today supply something like 0.14 watt-hours per gram, or seventy times less than fat. These are the lithium-polymer batteries, abbreviated "Li-poly". There are some other drawbacks to lithium-polymer batteries, such as safety, and a relatively short life in terms of the number of charge cycles they can endure. However, they offer the best solution available at the present time. Nickel-metal-hydride batteries can be used, but they have an even lower energy density. Nickel-cadmium batteries are worse still, and they have the added "benefit" of containing a deadly toxin. Are the Li-poly batteries starting to look better?

Just to touch on safety a little more, it's important to charge the lithium batteries correctly, so they don't start a fire. It is important to use special chargers designed for Li-poly batteries and for the particular size of battery you are using. (Use a cell-balancing charger with multi-cell packs. Otherwise, the battery will not last through many cycles.) Also, these batteries are ruined if you draw them down below a certain voltage, about three volts per cell. Special Li-poly compatible motor controllers will automatically shut the motor off to keep the battery from discharging excessively and dropping below that critical voltage. (Even better, for ornithopters, is a "soft-cutoff" feature, which reduces the throttle when the battery gets low.) When using these batteries, it's a good idea not to try to squeeze out an extra bit of flight time once you sense the battery is getting low.

Storage Medium	Energy Density (Wh/g)
Contest Rubber	0.007
Battery, NiCd	0.04
Battery, NiMH	0.07
Battery, Li-poly	0.14
Nitromethane	3.3
Methanol	6.4
Fat	10.5
Gasoline	12.2

Energy Density. Chemical fuels have much higher energy densities than electric or rubber power systems. Energy density is measured in watt-hours per gram.

Other Power Systems

Internal combustion engines have been used in ornithopters. Normally, a pull-start engine equipped with a centrifugal clutch and a large heat-sink would be used, similar to what would be found in an RC helicopter or car. The fuels, such as the methanol blend used in most RC engines, have a high energy density, about the same as fat. (Nitromethane has a lower energy density than methanol, but it increases the power output by causing more of the fuel to burn.) Despite the high energy density of the fuels, internal combustion engines are far less efficient than electric motors. Combined with the difficulties of starting, cooling, exhaust, and noise, this weighs against the use of internal combustion engines in most ornithopters. They should be considered for manned ornithopters, or in special applications where the required flight duration cannot be achieved using batteries.

Model airplane engines are air-cooled in order to save weight and reduce complexity. This works very well in airplanes, because the propeller keeps cool air flowing across the cylinder head. In an ornithopter, however, there is much less of a cooling breeze, and the engine is apt to overheat if special measures are not taken. The simplest approach, used in many RC cars and helicopters, is to use a special enlarged heat sink on the cylinder head, which provides a greater surface area for cooling. Another option is to use a fan to blow air across the cylinder head. This might save a little weight, but it is more complex and consumes power, which probably offsets any weight savings. Perhaps this method should be used in cases where it would not be possible for the heat sink to protrude outside the ornithopter body where it can receive adequate airflow. Both methods have been used successfully with ornithopters.

Another quirk of internal combustion engines is the difficulty of starting them. With airplanes, you flip the propeller to get the engine running. The propeller provides a convenient starter crank as well as flywheel. With ornithopters, because of the substantial gear reduction, one cannot start the engine by manually moving the wings. Instead, the impetus for starting the engine must be conveyed directly to the engine shaft, either by using a starter cone or pull-starter as in RC cars and helicopters.

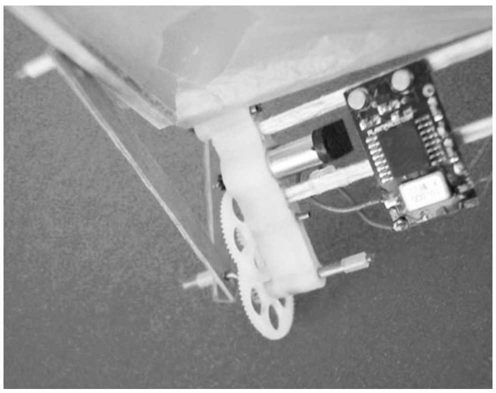
A third major problem with internal combustion engines is that they may stop unexpectedly and cannot be easily restarted in flight. An auxiliary electric motor may be necessary to level the wings for gliding. An electric motor could also be used to restart the engine in flight. A centrifugal clutch should be provided, so that the engine can idle without the wings flapping. This helps prevent the engine from stalling, since the load is removed whenever the engine speed becomes low. By subsequently increasing the throttle, it is possible to resume the flapping of the wings. Coupled with some kind of device to position the wings in a correct position for gliding, this system makes it possible for engine-powered ornithopters to glide when desired and then power-up again for flapping flight.

Compressed air or carbon dioxide can also be used to drive a piston motor. These motors have been used successfully to power ornithopters, but they don't have any particular advantage over electric power, apart from their intrinsic interest and vintage character. The reciprocating piston can drive a rotating flywheel and mild gear reduction, or the piston may drive the wings directly. The geared approach allows a greater power output from a given size cylinder, because the cycle rate is higher. Commercially available CO_2 motors, designed for model airplanes, can be used in this way. The piston-driven motors are powered by a small tank of compressed CO_2, which can be easily refilled before each flight. However, the direct-drive approach has been used in some experimental ornithopters, and commercially-produced toys, where custom-designed motors were possible.

In addition to these compressed-air cylinders, several other types of "artificial muscle" have been developed. These include hydraulics, pneumatics, "muscle wires" made of shape-memory alloys that contract when heated by an electric current, and special polymers that contract in an electric field. These systems have held great appeal for ornithopterists, but none of them offers a high enough power-to-weight ratio for flapping-wing flight. Similarly, some hobbyists have been tempted to use model airplane servos to flap the wings of an ornithopter. This is a convenient way to flap a pair of wings, but the power output falls far short of that required for flight. Someday, there will be a really powerful and efficient artificial muscle, and its existence will greatly accelerate the development of ornithopters. That day has not yet arrived.

Ornithopter Gear Design

There are two ways to build an ornithopter gearbox. The simplest method is to space the gear axles along a linear rail or strut. This method is recommended for micro-sized ornithopters, which usually don't have ball bearings. The other method involves two or more plates with spacers between them. Bearings can be pressed into the plates to hold the gear axles. The plate gearbox design is better for dual-crank mechanisms, and it lends itself to the more complex body designs typical of larger RC ornithopters. In either design, gears and drive cranks must be attached to their shafts very securely because of the high torsional loads they will encounter.



Strut Gearbox

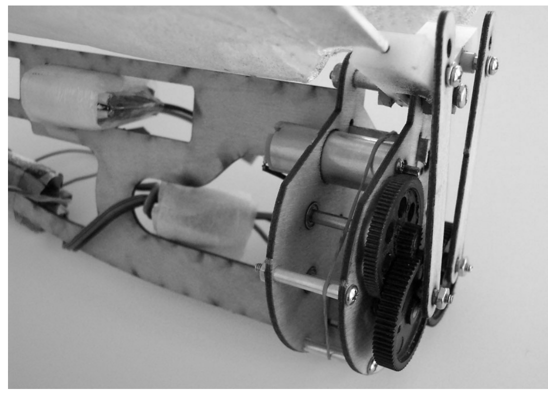
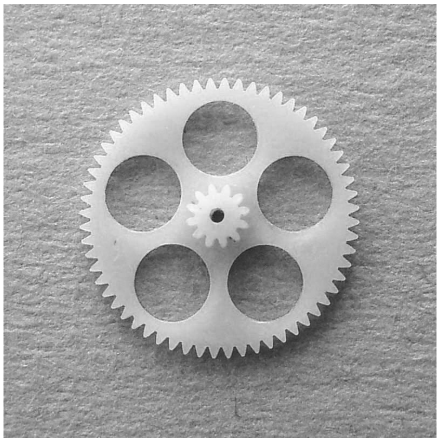


Plate Gearbox

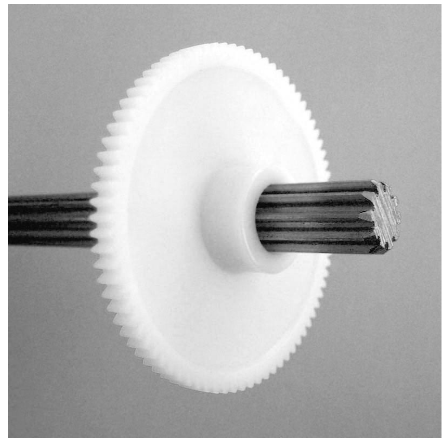
Spur gears, as shown, are the best choice for ornithopters because of their low friction. The vast majority of successful ornithopters have used spur gears. Planetary gears, harmonic drives, timing belts, chain-and-sprocket systems, and ball screws are other low-friction candidates. A chain drive might be considered for manned ornithopters. By distributing the load onto more of the gear teeth, the chain drive permits weight reduction, and it is nearly as efficient as spur gears. Ball screws require the motor rotation to be reversed at the end of each wing stroke, a serious liability, but this technique was used in the partially successful QN pterosaur project directed by Paul MacCready. You should avoid using worm gears. They might be tempting because they permit substantial gear reduction in a single stage, but the frictional losses are extremely high!

Lubrication should also receive some attention. Though some lubrication is probably better, plastic spur gears can be operated without lubrication, even when combined with metal pinion gears. On the other hand, if all the gears are metal, they should be bathed in lubricant. This is achieved by using a sealed gearbox with lubricant inside. The sealed gearbox also offers the benefit of noise reduction. However, by the time you have the metal gears in their sealed enclosure, it will end up being a lot heavier than the equivalent plastic gearbox. Most ornithopters use an open-frame gearbox design and plastic gears.

The limited supply of suitable gears long made it difficult to build electric-powered ornithopters. Recently, the plastic cluster-type spur gears from Didel have made it much easier to build gearboxes for ornithopter micro-air-vehicles. For larger ornithopters, gears are available from industrial suppliers like Stock Drive Products. Suitable cluster gears are not available in these larger sizes, and the small pinion gears typically don't fit the same shaft sizes as the larger spur gears. The solution is to put the large spur gear on a shaft made of "pinion wire". This provides a simple, lightweight solution for achieving substantial reduction ratios.



Cluster Gear



Spur Gear with Pinion Wire

Depending on the total reduction ratio you need, your gearbox might have one, two, or three reduction stages. A single stage gearbox is the simplest to build, but it usually won't provide enough gear reduction. Multiple stages add to the complexity of the gearbox but allow you to achieve greater reduction ratios without using excessively large gears. It's easy to calculate the total gear ratio. It is simply the product of the individual stages. For example, if the first stage is 5 to 1 and the second stage is 6 to 1, then the total reduction will be 5 x 6 = 30 to 1.

How much reduction is needed?

That will depend on your motor selection and what flight characteristics you want the ornithopter to have. It is important to understand the difference between power, speed, and torque. Torque is a rotational force. Speed is the number of rotations per minute. Power is speed times torque. By providing gear reduction, you can increase the torque of a motor, but this does not make it more powerful. It only adapts the motor to a different type of load. For example, a geared motor may be suitable for flapping large wings at a low rate, whereas the ungeared motor would turn a small propeller at a very high RPM.

One technique would be to vary the gear ratio until the greatest possible flapping rate is achieved. At first it may seem that if you hold everything else constant, the best gear ratio would be the one that flaps the wings fastest. That is your maximum power output. However, you need to be careful not to overheat the motor and battery. Therefore, you might need to use a little more gear reduction, to take some load off the motor. This will reduce the power output, but it will increase the run time and life of the power system.

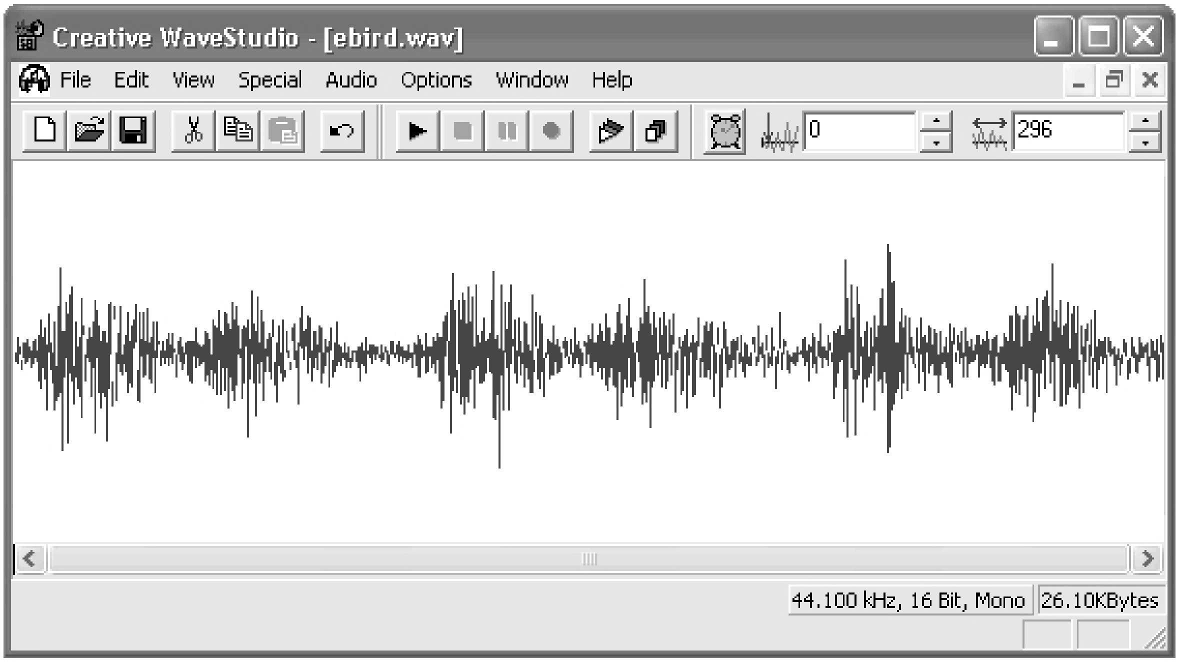
A more practical method of optimization is as follows. First, measure the flapping rate, and from this, calculate the motor speed. Compare this with the optimal speed of your motor. Then, adjust the wing size, flapping amplitude, or gear ratio to achieve the optimal motor speed. The phrase "optimal motor speed" might refer to the maximum power speed or the maximum efficiency speed, depending on your purposes. If you want your ornithopter to be efficient and fly a long time, then aim for the maximum efficiency speed. If your application requires rapid climbs or bursts of speed, then you can go for maximum power. Always keep in mind that the motor or battery may overheat if you try to run your system at the maximum power speed for any length of time. If you run the motor below its rated voltage, it is more likely to stay cool at the maximum power speed, whereas if you use a higher voltage, it is more likely to overheat.

The max power speed and the actual amount of power both increase with voltage, or with throttle setting, so you might consider optimizing the model for maximum efficiency at whatever throttle setting is found necessary for level flight. This would give you the longest possible flight times, while sacrificing top-end performance.

How to Measure the Flapping Rate

Several techniques exist for accurately measuring the ornithopter flapping rate. The method of choice depends on what equipment you have and what environment you are working in. Model airplane enthusiasts use an optical tachometer to measure the rotational speed of their propellers. This device senses the sunlight passing through the propeller disk, which is interrupted twice for every revolution of the propeller. These devices work poorly for ornithopters, because they were not designed for the relatively slow motion involved. They do not work with artificial lighting because of the 60 hertz (Hz) cycling of the electrical supply. With battery-powered lighting and some reflective tape, it is possible to directly read the motor RPM of an ornithopter with an optical tachometer, but luckily you have other options.

The stroboscope is an electronic device consisting of a flashing strobe light and equipment for precisely controlling the flashing rate of the light. You can measure the flapping rate of your ornithopter by synchronizing the strobe rate with the flapping rate of the ornithopter, and then reading the strobe rate from the device. The stroboscope (or even a cheap party strobe light) is also useful as a way to observe what the wings are doing as they move through the flapping cycle under load. When the strobe is synchronized with the wings, the wings appear to stand still, and you can also watch the wings flap in slow motion. Stroboscopes require fairly dark conditions in order to be useful. Another disadvantage is the cost.



Computers are expensive, too, but you probably have one already. If so, you can use your computer to measure the flapping rate. This is the method that I use most often. It is very accurate, and you only need a short burst of flapping to get a good measurement. You will need a microphone and sound-editing software that shows a graphical display of sound volume over time. You simply record sound into the computer, and afterwards use the sound-editing software to measure how much time elapsed during a given number of wing beats. Typically, the sound volume peaks twice in each flapping cycle because of the increased gear noise at the end of each wing stroke. In the example shown here, three flapping cycles have been selected, and the computer tells us that 296 milliseconds have elapsed. Divide three flapping cycles by 0.296 seconds to get the flapping rate of 10.1 cycles per second (Hz).

A final option is to simply train yourself to judge the flapping rate accurately with your own eyes and ears. To do this, you need feedback: a way of knowing whether you're right or wrong. For this purpose, there is a special computer program at the Ornithopter Zone web site. Go to www.ornithopter.org, and click on the "software" link.

Gear Sizing Standards

If two gears are to mate properly, they must have the same size teeth. The company you buy the gears from should provide the necessary information, but there are various sizing conventions you will need to understand. For inch-sized gears, the size of the gear teeth is indicated by a number called the "diametrical pitch". The number of teeth on a particular gear is related to the diameter of the gear. For example, if the gear has a diametrical pitch of 48, then the number of teeth is 48 times the gear diameter in inches. We are not talking about the outer diameter of the gear, but the “pitch diameter” where the opposing gear teeth are supposed to make contact. A one-inch gear would have 48 teeth. Larger numbers indicate smaller teeth.

Metric gears use a different system. For these gears, the size of teeth is indicated by the “module” size, which is the diameter in millimeters divided by the number of teeth. For example, if a gear is 20 mm in diameter and has 40 teeth, this would be a 0.5 mod gear. Notice that a 0.5 mod gear has larger teeth than a 0.2 mod gear, whereas in the inch system, a larger number means smaller teeth.

Whether using inch or metric gears, the pitch diameter is used to calculate the gear spacing. For two meshing gears, add the pitch diameters together and divide by two. For example, if one gear has a pitch diameter of 0.5, and the other has a pitch diameter of 3.0, the center-to-center distance between axles should be 1.75.

$$\begin{aligned}\text{Distance} &= (Dp1 + Dp2) / 2\\ &= (0.5 + 3.0) / 2\\ &= (3.5) / 2\\ &= 1.75\end{aligned}$$

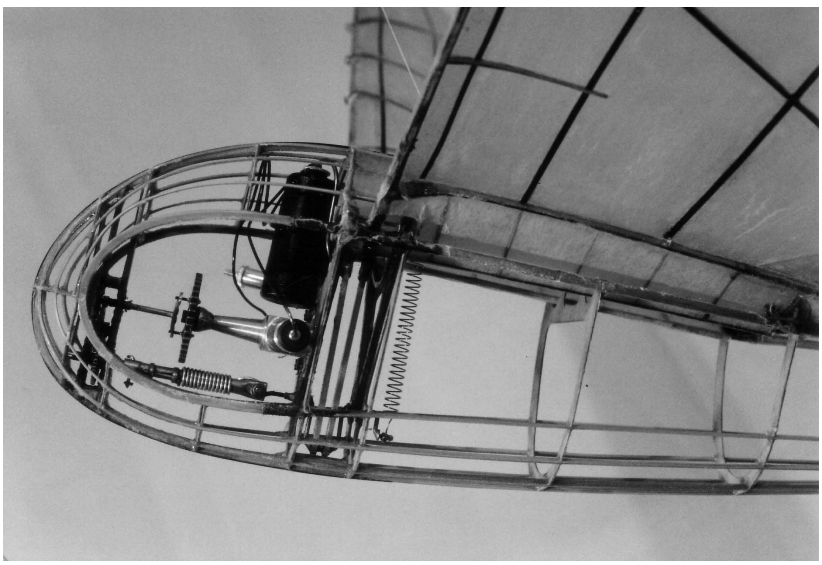
In principle, the calculated distance should result in minimal friction between gears. However, due to imperfect manufacturing of the gears, you might find that a slightly larger spacing is appropriate. For example, the Didel gears used in micro-sized ornithopters should have about 0.02 to 0.04 mm of extra space in order to turn freely. If you aim for a spacing slightly larger than the calculated distance, this will also protect you from inaccuracy in your spacing of the axles. If the gears mesh too tightly, they will not turn freely. If the gears mesh too loosely, they might skip under load, but you have a little more room for error in that direction.

Gears are designed for different pressure angles. This is the angle at which the gear surfaces make contact. The pressure angle determines the profile shape of the gear tooth. A lower pressure angle is more efficient. However, a higher pressure angle results in a stronger gear. Meshing gears must be designed for the same pressure angle, or the teeth will rub against each other, causing wear and friction.

Energy Handling Devices

In addition to gear reduction, there are several other energy-handling devices that may be used in electric or engine-powered ornithopters. The most important of these is perhaps the flywheel. The flywheel causes the engine to run at a relatively constant speed, resulting in greater efficiency and, in the case of internal combustion engines, decreased likelihood of the engine quitting. The flywheel also acts as an energy reservoir. When there is little or no load on the motor, during the upstroke or between strokes, the flywheel accelerates, gaining energy, and when there is a larger load, during the downstroke, the energy stored in the flywheel is imparted to the wings. The effectiveness of the flywheel increases with its mass, but increases even more with its diameter and speed. Normally, electric-powered ornithopters do not require a separate flywheel, because the motor acts as a flywheel. Outrunner-type motors tend to have more of a flywheel effect than inrunners, so they provide a smoother flapping motion.

Regardless of power source, a spring may be used to assist the downstroke. This technique only makes sense for monoplane ornithopters, but it has been used with rubber, CO_2, electric, and engine-powered ornithopters. This device performs much the same function as the flywheel, in that it stores energy during the upstroke and imparts it to the downstroke. Since the spring reduces engine speed fluctuation, it may reduce the need for a flywheel. Oddly enough, whenever I have tried this technique in electric ornithopters, it always seems to reduce the flight performance. The springs inherently consume more power than they release, and they might also increase the amount of wing hinge friction. The flywheel effect of the motor seems to be more what the ornithopter needs.



This CO_2-powered ornithopter from Joss Levy exhibits a flywheel, a tension spring for balancing the force of lift on the wings, and a torsion spring for maintaining a constant drive torque.

A third device is somewhat controversial, but it too has been used successfully. This is the drive train torsion spring: a spring located right in the ornithopter drive train so that it winds up as motor torque is applied. The unwinding of the other end of the spring drives the wing flapping. This allows a more constant motor speed than would be possible with a flywheel alone. The torsion spring converts the constant speed output of the motor to a constant torque output not unlike that of a rubber motor. The constant-torque flapping might be more effective, since the wing is driven forcibly right to the conclusion of the wing stroke. However, there are two disadvantages here. First, the constant-torque output will result in a rapid upstroke, which reduces the amount of lift that can be produced in the upstroke. Second, the unloaded crank can jump forward at the end of each wing stroke, wasting some energy and increasing the stress on the mechanism. More people should try this so we can get a better sense of whether or not it is beneficial overall.

Design of Manned Ornithopters

Although arguments have been made for the superior fuel economy of flapping wings, perhaps the two greatest reasons for developing the manned ornithopter were to prove that it could be done and to offer humans the experience of flying like a bird. Now that some flights have been made, it is necessary to develop a more comfortable and reliable machine so that more people can enjoy that long-sought experience. Some have suggested that manned ornithopters would be too complex to be practical. However, helicopters are equally complex.

There are two types of manned ornithopters: those powered by the pilot's own muscles, and those powered by some type of engine. Although the muscle-powered type has held great appeal for wishfully-thinking designers, the fact is that engine power is much more practical and more likely to yield success. Muscle-powered *airplanes* are only marginal, and I see no reason why muscle-powered ornithopters would do much better.

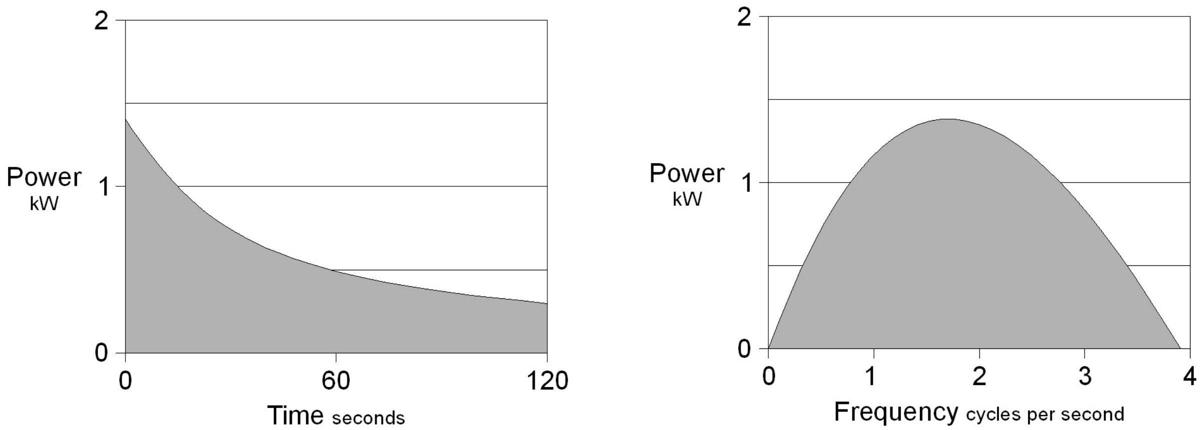
Human muscle power drops off rapidly over time. The maximum short-term power output will depend on the person, and it won't be any higher than about 1 kilowatt even for a trained athlete in a short burst. (A model airplane motor the size of your fist can produce more power than this.) A rowing motion is typically used, because this allows the muscles of the arm and torso to contribute to the effort. With only foot pedals, you don't get as much power.

Any aircraft needs a certain amount of power for sustained flight. Since muscle power drops off over time, the pilot/athlete can maintain the necessary level of power only for a specific period of time, which might be very brief. For this reason, it has been difficult to distinguish between a brief, successful flight, and a brief flight in which the aircraft did not quite sustain itself after an assisted launch.

In order to demonstrate a "sustained" flight, not only the speed, but also the altitude, must be maintained for some brief period of time. In other words, the sum of potential and kinetic energy must not decrease. If you plan to make a muscle-powered ornithopter flight, you should arrange to measure the speed and height simultaneously at least twice during the flight so you can demonstrate conclusively whether a sustained flight is achieved. The possible effects of wind should also be taken into account.

One of the attractions of muscle power has been the perceived potential to link the pilot directly to the wings, without any need for gear reduction or mechanisms to convert rotary to reciprocating motion. There may be some real advantages, such as being able to exert more force at specific times in the flapping cycle when it is needed most, and conserve energy at other times. However, the direct linkage has a serious problem. Like electric motors, our muscles can produce their maximum power output only when operating at a certain frequency. For humans, the maximum power frequency is about 1.7 Hz in short bursts of rowing. This is probably a bit high for a human-powered ornithopter flapping rate.

Human Muscle Power Output



Some techniques have been used to bring the flapping rate in line with the maximum power frequency. One is to use a shallow flapping amplitude, perhaps inefficient, and the other is to flap a relatively small portion of the total wing area.

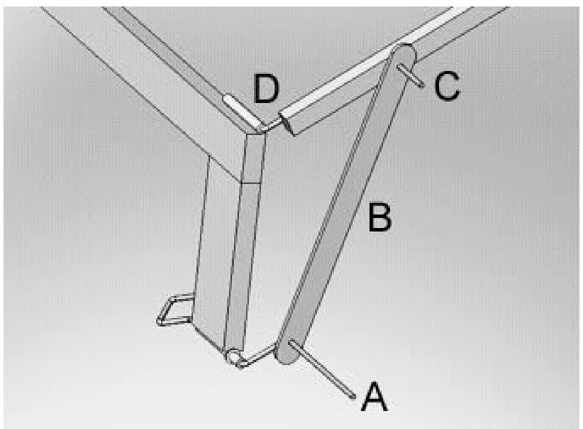
With any manned ornithopter, you'll want to provide a smooth ride for the occupants of the vehicle. The easiest way to do this is with a biplane or tandem configuration. The opposing action of the wings should be designed to minimize oscillation of the ornithopter body. It may also be possible to reduce body oscillations by adjusting angles of attack along the wings. For example, the downstroke inner part of the wing lift would be decreased so that a constant lift force is maintained throughout the flapping cycle. Karl-Heinz Helling's SF-8 unmanned ornithopter had a single rigid wing that moved straight up and down. A gyroscopically-controlled mechanism adjusted the angle of attack to maintain a constant amount of lift.

Safety should be given very careful consideration when testing manned ornithopters. I cannot provide a complete set of safety guidelines, but I will make a few suggestions based on the experience of others. First, do not launch from a high place. People have died this way. Even a tow launch entails substantial risk, because the aircraft is placed at a height before determining whether it can fly. To reduce the likelihood of incidents, or at least minimize the altitude at failure, the ornithopter should take off from the ground under its own power. Likewise, controllability should be proven before taking on significant altitude. The pilot should be seated and enclosed in a strongly built cockpit, with appropriate safety equipment, including a restraining device, helmet, etc. A prone pilot position should never be considered, as it has resulted in very serious injuries. Certain biplane ornithopters are probably safer than monoplanes because the wings may continue to support the aircraft in the event of a linkage failure. There are also specific safety and licensing requirements imposed by governments. Regardless of any safety measures, experimental aircraft are inherently dangerous. Proceed at your own risk.

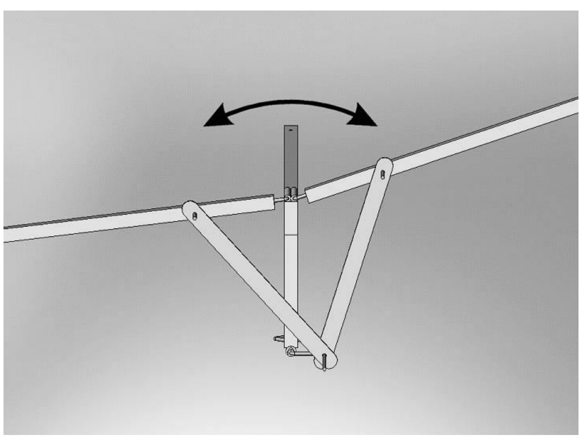
Flapping Mechanisms

The purpose of the flapping mechanism is to convert the rotary motion of your motor into the reciprocating motion of flapping wings. There are many ways to do this, and I will describe only some of the more common ones here. The mechanism must be lightweight and fairly simple. Yet it must also provide a fairly symmetrical wing motion so the ornithopter flies straight.

The basis for most mechanisms is the “crank-rocker” type of four-bar linkage. Here, the motor drives a rotating crank. The crank has a connecting rod attached to it, and the other end of the connecting rod is attached to the wing. As the crank goes around, the connecting rod pushes the wing up and down.

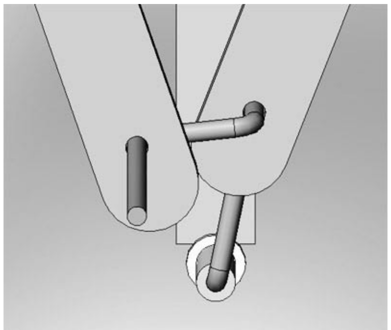


The crank (A) rotates, causing the connecting rod (B) to move up and down. This connecting rod attaches to the wing lever (C), causing the wing spar to flap up and down at the hinge point (D).

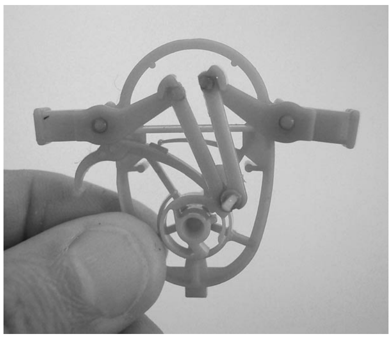


When a second wing is added, each wing lever “sees” the crank from a different vantage point. The angle between wing levers results in a timing difference between the two wings.

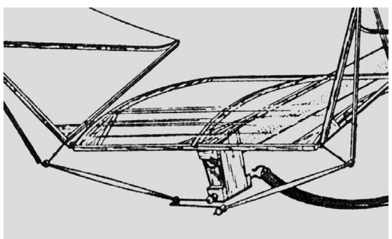
Unfortunately, when a second wing is added, the simple four-bar mechanism will produce asymmetric flapping. The two connecting rods leave the crank at different angles. This causes them to act at different times. The timing difference can be expressed in degrees of crank rotation. For example, the wings might have a timing difference or "phase shift" of 30 degrees. The asymmetric flapping lowers efficiency and makes the ornithopter want to turn to one side. The difference in timing between wings is called the “lead-lag” effect.



Staggered Crank: The simplest solution to flapping asymmetry is the staggered crank. The great advantage of this mechanism is that it uses the single-strut body structure shown on the previous page. Here, the connecting rods go off at different angles, but their timing is corrected by having them placed on separate crank throws. The crank itself is most easily constructed from bent wire. This normally limits this mechanism to fairly small ornithopters.



Outboard Wing Hinges: If your fabrication methods will not allow a staggered crank, it might be preferable to separate the two wing hinge lines so that the connecting rods pass together between the wing hinges. Since the angle between the connecting rods is small, the flapping is fairly symmetric. Unfortunately, you will need a more complicated body structure to support the outboard wing hinges.



Fully opposed crank throws: Common in older designs, this mechanism combines the worst features of those preceding: It requires a double-throw crank and outboard wing hinges. This time the crank throws are 180 degrees apart from each other, reflecting the more divergent wing lever locations. Quite symmetrical flapping is possible.

Dual Cranks: Another solution is to use two completely separate cranks. This requires an additional drive shaft and gear. This mechanism will probably weigh a little more than the other mechanisms shown above, but the flapping will be more symmetrical, while avoiding the difficulty of making a double-throw crank.

Transverse Shaft: A variation on the dual crank idea is to use a single, transverse drive shaft, with cranks at either end. This simplifies the design and saves weight. Since the cranks are not operating in the same plane as the flapping arc, the connecting rods must have ball joints at their ends. This results in more friction compared with ball bearings operating in a single plane.

The consequences of the lead-lag effect are several. First of all, flapping asymmetry imparts a rolling moment on the craft, which gives the ornithopter its characteristic built-in turn. Another effect is the loss of energy. If your model rolls from side to side with every flap of the wings, it is expending energy without doing any useful aerodynamic work.

It should be pointed out that the actual amount of asymmetry, or in other words, the phase difference between wings, will depend on the particular dimensions of the flapping mechanism. You can improve the symmetry by increasing the vertical distance between the crank and wing hinges. In some cases, this might be the only corrective measure necessary.

There are several other ways to achieve a more symmetric wing motion, all described on the previous page. These are the most commonly used mechanisms for two-winged (monoplane) ornithopters. A wide variety of other mechanisms have been developed for special purposes, such as flapping multiple wings, moving the tail along with the wings, folding the wings on the upstroke, or actively twisting the wing structure as it goes through the flapping cycle.

Dead-Center Effect

Particularly in rubber-powered ornithopters, the crank mechanism is not an ideal method for converting rotary to reciprocating motion. The problem occurs at the end of each wing stroke, when the crank arrives at its “dead center” position. Here, the crank arm and the connecting rod are directly in line with each other. The crank continues its rotation, but momentarily it is not doing any work on the connecting rod or the wings, which have come to rest and are about to go back the other way. There is no resistance on the crank. The crank, freed of the aerodynamic and inertial load, as well as given a huge mechanical advantage by the fact that the connecting rod now lies parallel to the crank arm, rapidly jumps forward.

This sudden acceleration of the crank, and the subsequent deceleration of the crank when the load is restored, cause tremendous "shock loads" that can tear an ornithopter apart if it is not properly constructed. The need for greater durability may add weight and reduce performance. Since the rubber band is unwinding without doing any useful work, the dead-center effect also constitutes a significant loss of energy.

The dead-center effect is worsened by looseness in the membrane, excessive play in the flapping mechanism, or by too much flexibility in the model structure or wing spars.

The dead-center effect can be mitigated by imposing a load on the crank. One way to do this is through asymmetric flapping of the wings. If there is a timing difference between the two wings, one will impose a load on the crank while the other is turning around. In other words, the two connecting rods do not line up with the crank at the same moment. This is not a perfect solution though, because the asymmetric flapping itself is not desirable. Another technique is to flap the tail out of phase with the wings, so that the linkage driving the tail imposes a load while the wing cranks are at dead-center. Biplane ornithopters are often designed so that one pair of wings is under load while the other pair goes through dead-center. Any of these methods will result in smoother and quieter operation.

The dead-center effect is mainly a problem for rubber-band-powered ornithopters. If you have an electric motor, the rapidly spinning part of the motor acts as a flywheel, so the crank cannot jump forward as it goes through dead-center. Instead, the motor may gain some speed, but that energy is stored in the flywheel, and it is smoothly transferred to the wings during the next wing stroke.

Lockup

Lockup is another potential problem with ornithopter mechanisms. Unlike the lead-lag and dead-center effects, lockup does not affect the majority of mechanism. However, when it does occur, this is a catastrophic failure that will stop your ornithopter from flying altogether and perhaps destroy the flapping mechanism. Lockup is avoided by having the correct dimensions for the flapping mechanism.

Lockup occurs when one or both wings flap too far in one direction and jump outside their normal range of movement. For example, if a connecting rod is too long, the wing may rise too far, to a point where the connecting rod is straight in line with the wing spar. From this awkward position, the wing takes an errant path, swinging over the back of the ornithopter instead of flapping back down again. The wing remains stuck in the wrong position, and the ornithopter cannot fly.

This problem can be avoided by making sure the connecting rod never reaches that position in which it is parallel to the wing lever. Since no mechanism is perfectly rigid, it is a good idea to plan the mechanism so that a safe angle is maintained between the connecting rod and wing lever. The following procedure for linkage design insures this, as well as allowing you to plan other dimensions of the flapping motion prior to construction.

Planning the Linkage Dimensions

While not always necessary, it is a good idea to design your flapping mechanisms on paper before building them. This will save you a lot of frustration, because you wouldn't want to spend many hours building something, only to find that it doesn't work. As an example of the process, I will use the mechanism with outboard wing hinges shown a few pages back. The same procedure will work with other mechanism types.

The first step in linkage design is the selection of the wing sweep angle (amplitude, indicated by the letter A in the diagram below) and average dihedral (B). As discussed in Section II, the dihedral angle is the angle between the wing and the horizon. Think of the wings being held in a slight “V” as seen from the front of the aircraft. Airplanes often have a certain amount of positive dihedral, which provides lateral stability. With ornithopters, the dihedral angle is constantly changing as the wings flap. (If you like, wing flapping can be defined as a cyclical change in dihedral angle over time.) For proper lateral stability, ornithopters require the *average* dihedral to be slightly positive. Thus, the midpoint of the flapping arc or wing sweep should be about 10 degrees above horizontal. The flapping amplitude may be anywhere from 20 degrees to about 100 with the mechanisms we have discussed. Most ornithopters have amplitudes between 45 and 60 degrees, but the optimum depends on the particular model: not just the wing design, but also the motor and gear ratio.

Next, decide on the amount of horizontal space between the wing hinges. In the diagram below, this is indicated by the letter "C". For the staggered crank mechanism, you want the hinges as close together as possible. For the mechanism with outboard wing hinges, you need to provide enough space for the wing levers to operate. This is determined by the size of the model and should be at least one tenth of the wingspan. (If the mechanism is too compact, the stresses on mechanism components will be excessive, as described below.) Also select the height, D, of the wing hinges above the crank axle. This is usually about half of the shoulder spread, but it may be greater.

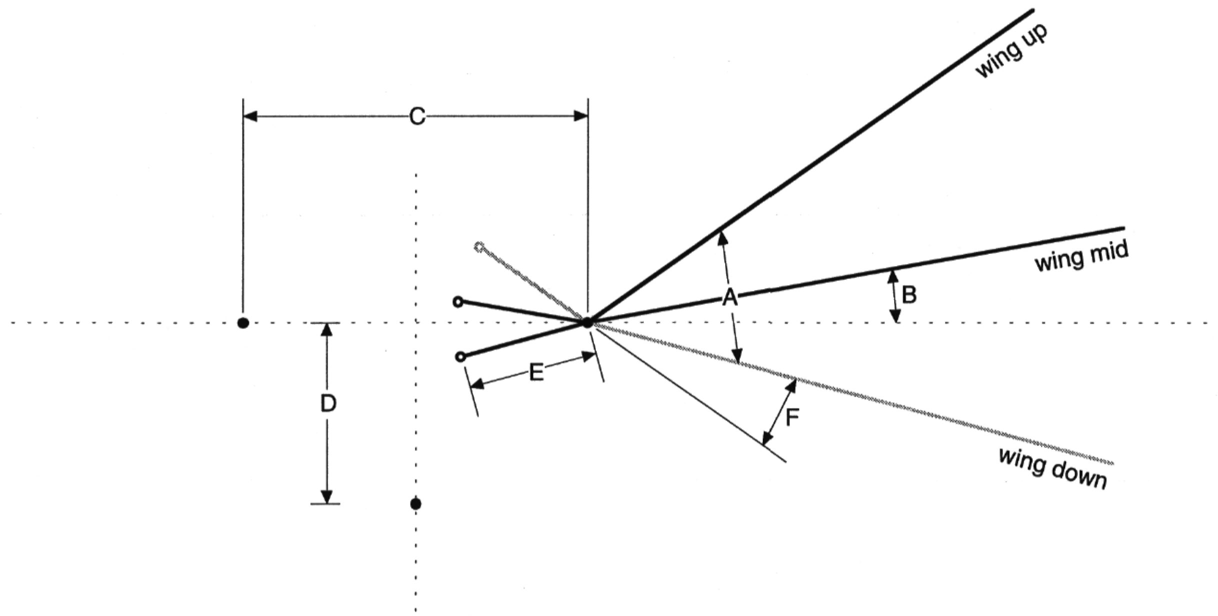
Once you have selected the required dimensions, draw the wing hinge points and crank center on a piece of graph paper, with the distances accurately to scale. Then draw the wings in their uppermost and lowermost positions. (For simplicity, I have drawn only one wing in its upper and lower positions. You may do the same.)

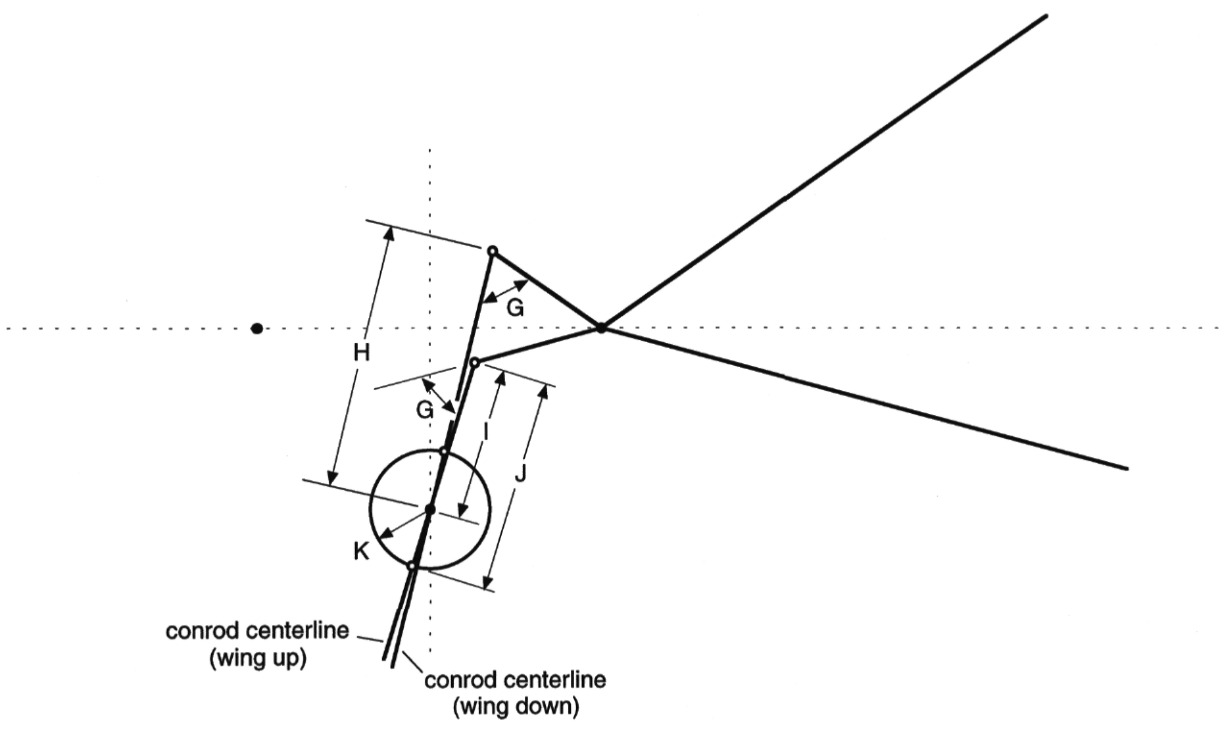
Now, select the wing lever radius, E. This should be at least one tenth of the wing spar length, to minimize the forces acting on flapping mechanism parts. Short wing levers require more force to flap the wings. The extra force is readily available by decreasing the crank radius. However, the larger forces would result in greater friction and stress, and any play in the mechanism will have a greater effect if the crank radius and wing levers are too short. The wing levers must be short enough to avoid colliding with each other. My simplified diagram shows each component as a straight line, but you will need to take into account the dimensions and possible inaccuracy of the actual parts, in order to insure proper clearance.

The distance between the left and right wing levers, along with the shoulder height, determines the angle between the connecting rods and thus the phase difference between the wings. Therefore, you will want to keep the clearance fairly small. You can even overlap the wing levers, as long as one is in front of the other so they don't collide. In most cases, this is not justified by the additional complexity that would result.

With the outboard-hinge mechanism, a wing lever offset angle (F) is usually required to prevent wing lockup. This is the angle between the wing spar and the wing lever. An angle of about 20 degrees is usually suitable. To determine whether or not lockup is likely to occur, first draw the wing lever, with an assumed offset angle, for the upper and lower wing positions. Then draw the connecting rod, as shown in the lower illustration. The connecting

Designing an Ornithopter Flapping Mechanism





rod should pass through the center of the crank, because we are drawing the mechanism in the upper and lower dead-center positions we talked about earlier.

For both the raised and lowered positions, the angle (G) between the wing lever and the connecting rod should be at least 30 degrees to insure that the wings will not lock up. If 30 degrees seems excessive, keep in mind that other crank positions will have a lower angle. Also, there is inevitable structural flexibility, and a small deformation of the structure could result in a large decrease in angle G. A low angle here is undesirable anyway, because it gives the crank a very poor mechanical advantage with which to start the wing moving again at the beginning of the stroke.

If angle G is less than 30 degrees in the raised wing position, this can be corrected by increasing the wing lever offset angle, by decreasing the amplitude, or by decreasing the average dihedral angle. Wing lockup at the end of the downstroke is less common and would indicate that the spar offset angle or the amplitude is too high.

When building your ornithopter, you will need to know the correct length for the connecting rods. To determine this, first measure the distance, H, from the crank center to the fully raised wing lever. Then measure I, the distance from the crank center to the lowered wing lever. The connecting rod length, J, is half the sum of H and I.

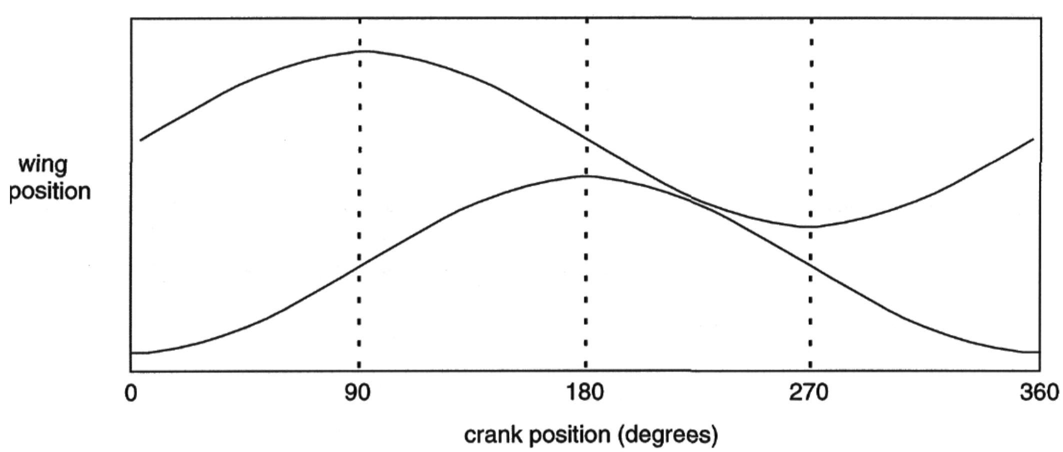
Next, you can determine the appropriate crank radius, K, and draw the circular path of the crank arm on your diagram if you so desire. The crank radius is equal to half the difference between H and I. If you wish, you may now draw the wing and linkage positions for any intermediate point in the flapping cycle. If you want to see where the wing will be at a particular crank position, first draw the arc made by the wing lever. Then draw the connecting rod by measuring a line of length J from the specified crank position to the wing lever arc. (You can use this method to assess angle G at various crank positions.) If instead you want to find out where the crank will be for a given wing position, draw the wing lever first and then draw a line of length J from the wing lever to the crank path.

It is interesting and instructive to work through this process on paper a few times. However, you may find it tedious if you want to try out several variations on a flapping mechanism. To speed the process, I have developed a simple computer program called FlapDesign. FlapDesign runs from the Ornithopter Zone web site (www.ornithopter.org), and it is very easy to use. You simply type in the dimensions of the mechanism, and then you can view the resulting wing motion as an animation or graph.

Biplanes

Biplane mechanisms operate in much the same way as monoplane mechanisms. The simplest biplane mechanism is no more than a single pylon mechanism with each wing spar extended out the opposite side of the model to form an extra wing. This four wings operate like a pair of scissors, so only two connecting rods are needed to drive them. Some dihedral must be built into the spar. While this mechanism still suffers from the dead-center effect, it is a great improvement over the monoplane. The 180 degree phase difference between wings (so that one wing is going up while the opposite wing is going down) results in more continuous lift and far better efficiency than monoplanes. There are some even better arrangements, though, so this one is seldom used in competition.

Most biplane designs have two crank positions and four connecting rods, one for each wing. This approach is obviously more complicated than the two-connecting rod, single-crank mechanism described above, but it offers several advantages. First, having a separate connecting rod for each wing allows the upper and lower wings to be 90 degrees out of phase with each other, as shown below. This technique, developed by John White, totally eliminates the dead-center effect, because the upper wings are at their greatest rotational speed right when the lower wings are changing direction. Additionally, this phase difference allows the upper and lower wing sweeps to overlap. The overlap allows the average wing position to stay closer to horizontal, while maintaining the same flapping amplitude. This increases the effective wing area and lift. Unfortunately, the 90 degree phase difference does not allow complete balancing of the upstroke and downstroke.



The phase difference between upper and lower wings is 90 degrees. The graph shows how the arcs of the upper and lower wings overlap.

Notice that phase differences other than 90 or 180 degrees are mechanically possible. It might be advantageous to use a phase difference of about 135 degrees. Halfway between 90 and 180 degrees, this phasing would minimize the dead-center effect while maintaining good counterbalancing of the up and down strokes. Any desired phasing can be produced, simply by modifying the crank.

It is also possible to combine 90 and 180 degree phasing in the same model. This is done by putting the left and right sides of the ornithopter out of phase with each other. For example, the upper and lower wings on each side might be 180 degrees out of phase with each other, but there would be a 90 degree phase difference between left and right sides. (Alternatively, you could have a 90 degree phase difference between upper and lower wings, but have the left and right sides 180 degrees out of phase with each other.) Unfortunately, there will always be some imbalance in the forces produced at any given moment, causing the ornithopter to roll or yaw back and forth as it flies. These imbalances cause some wasting of energy, but the various phased biplane designs have proven themselves in competition.

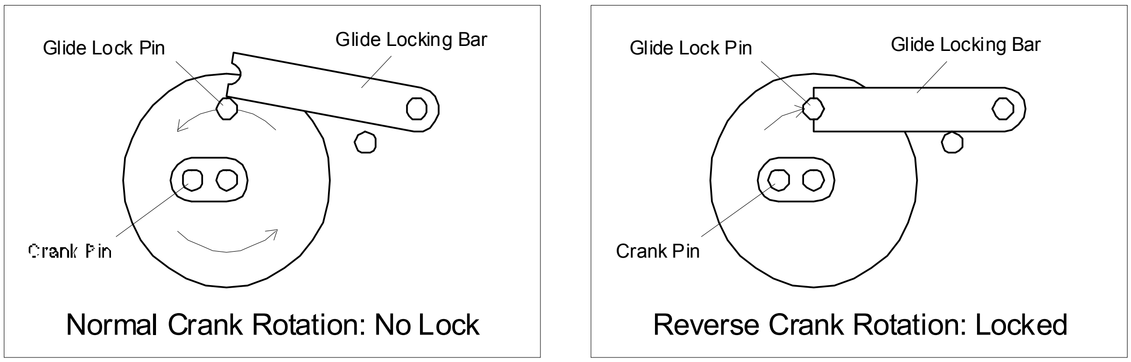
The design of biplane linkages is more complex than the design of monoplane linkages, because there are twice as many wings and because one must insure that the wing pairs do not interfere with each other mechanically. The planning procedure described above may be used with appropriate modifications for biplanes. Since the upper and lower wings might not be 180 degrees out of phase with each other, it is not always necessary for the fully raised position of the lower wing to be below the fully lowered position of the upper wing. For example, the upper wing may briefly move down into a space which will later be occupied by the lower wing. In order to confirm that no wing collisions will occur, you can use the following procedure: First, find the crank positions where the lower wing is fully raised and where the upper wing is fully lowered. Then draw the crank position halfway between those two crank positions. This is where the wings are most likely to collide. Finally, draw the positions of the upper and lower wings for the intermediate crank position. (This method assumes that the upper and lower wing amplitudes are the same, which need not be the case.)

Glide Devices

To achieve a fairly good glide, the wings should be held in a horizontal or slightly dihedral position. This will add a good deal of complexity, so it is often not implemented.

In rubber-powered ornithopters, there is no need to release the glide locking device during flight, so it is relatively simple. The Tim Bird toy has a slotted barrel on the crankshaft, and a pin grabs the slot as the crank rotation slows. If used in a radio-controlled ornithopter, you would need an additional servo to disengage the latch prior to restarting the motor. Another mechanism has a small compression spring under the crank bearing, which pushes the crank forward as the rubber band unwinds. Then some portion of the crank wire or motor hook catches on some target attached to the body frame, causing the crank to stop at a specific spot in its rotation.

The simplest method for RC ornithopters is to use a ratchet-type mechanism which allows the normal forward rotation of the crank, but blocks the crank at a pre-determined glide position when the crank rotates backwards. This method is not consistently reliable. Only if the wings happen to stop in the lower portion of the downstroke will the force of lift on the wings cause the crank to rotate backwards and engage the locking bar. Therefore, the reliability is about 1 in 4.



Mechanical glide lock mechanism as developed by Sean Kinkade.

The reliability can be improved in several ways, but with increased cost and complexity. One idea would be to use a bi-directional speed control, so that you can reverse the motor on command. However, the bi-directional ESCs used in RC cars are very heavy, and aircraft radios are not set up to work with them. The risk of accidentally applying full power in reverse (and thus destroying the mechanism) would be unacceptably high. A second method would be to time the stopping of the motor just right, so the wings always stop in the lower downstroke. Robert Korobelnik of France has developed a special electronic device that senses the crank position and, after you turn off the throttle, applies low power to the motor until the correct wing position is reached. This greatly improves the reliability of the mechanical locking bar.

Construction of Flapping Mechanism

The core of a rubber-powered ornithopter is the motor stick, and this is likely to be the first part you build. Ornithopters generally require much more torque than airplanes, so the motor stick must be quite strong to prevent it from bending, twisting, or breaking under the tension and torque of the rubber band. The lightest indoor models use hollow balsa tubes for motor sticks, while in most other models, solid balsa is used. Serious indoor competitors sometimes use fine tungsten wire to brace the motor stick.

The thrust bearing, which supports the crank wire against the tension of the rubber motor, may also need to be extra strong in ornithopters due to the relatively thick motors used. In very light models, the same aluminum brackets used for indoor airplanes are appropriate. Otherwise, an aluminum or brass tube is commonly used as a mount for the crank shaft.

Ends of the tube must be perfectly smooth, or the crank will get caught at specific spots during its rotation. The tube must be prevented from pulling loose due to motor tension, so it may be strapped to the fuselage with thread or layers of tissue paper and glue. Grooves filed into (but not through) the tube wall will help prevent slippage in heavier models. In larger models, the flanged nylon bearings sold for rubber-powered airplanes may be used.

A small plastic or glass bead is placed on the crankshaft to reduce friction between the crank and the mounting bracket. The inside hole must be small enough to prevent the bead from traversing the bend in the crank. A teflon washer may be added between the bead and the mounting bracket to further reduce friction. Do not underestimate the importance of the crank bearing. If the crank bearing in a rubber-band-powered ornithopter is not properly constructed, the ornithopter will not fly.

The flapping mechanism also encounters great stress due to the flapping of the wings. Glue joints should be reinforced with tissue or thread, as was done for the crank bearing. Attention should be given to the design of hinges in order to minimize friction and maximize strength.

The illustration shows a variety of hinge construction techniques useful in ornithopter flapping mechanisms. These are suitable either for rubber-powered or small electric ornithopters. Hard steel music wire is used for the hinge pins. The connecting rods are usually made of balsa wood or model aircraft plywood. If balsa wood is used, the wood around the hole is soaked with glue to provide a harder bearing surface. For large RC ornithopters, a more robust method of hinge construction is be required, and such techniques are described later. To some extent, the choice of hinge design should reflect the size and weight of the ornithopter. However, it also reflects the tastes of the individual designer. This is one of the hints that often make it possible to guess who designed a particular ornithopter just by looking at it.

In the Freebird design, you saw how metal tubes can be used in a wing hinge. In the lightest indoor models, the tube is made of tissue paper. The tube is created by coating a small piece of tissue with glue and rolling it up. You can roll it onto a steel wire core and then remove it after the glue is completely dry. (Use a glue that doesn't stick to metal.)

Instead of tubes, you might prefer to use a thin aluminum plate with a tiny hole in it. You can buy these from indoor model suppliers, or you can make your own from thin sheet aluminum. The flat aluminum piece can be driven into the end grain of a balsa stick to provide secure fastening. Roughen the metal surface with course sandpaper, and use a water-based glue to avoid toxicity. Another option is to bind the aluminum piece onto the outer surface of the balsa and secure it with tissue or thread.

The wing frame may consist of the spar alone, as in the Freebird, or there may be a more complicated, L-shaped frame with diagonal bracing. The simpler method requires a sturdy wing hinge that can prevent the spar from swinging backward. The bent wing lever wires of the Freebird offer a flexible, impact-resistant wing hinge, together with an attachment point for the connecting rods. This is fairly heavy, however. With the braced, L-shaped frame, the wing is supported from swinging backward by providing separate front and rear hinges for the wings. Since each of these hinges can be simple and light, this is probably the better option for contest models, though it is more complicated to build.

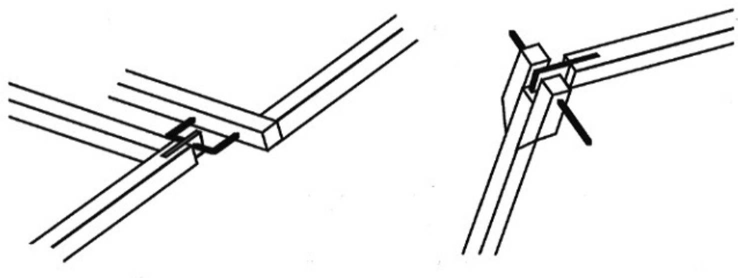
You can save weight again by using separate, straight wire segments for the wing hinge and for the attachment of the connecting rod to the wing. For the wing hinge, music wire is typically driven into the pylon and glued in place. The other end of the wire pivots in the wing spar. If the wing lever is constructed from a separate piece of wood, the wing hinge wire can be inserted through the scarf joint for extra strength. Some effort is usually made to harden the area around the hole, for example by soaking some glue into the wood or by gluing a layer of tissue around the wood. Using similar construction, a music wire pin joins the connecting rod to the wing lever. The wire may be glued to either part and pivot within the other. Some modelers prefer to have the pin mounted in the wing lever. This allows easier replacement of connecting rods if they are broken or the wrong size.

Another lightweight hinge can be made with thread. Thread hinges can be very light, low in friction, and durable, but they are difficult to build, and you have to be careful to avoid excessive play in the hinge. You can also use the wing tissue itself as a hinge, adding some reinforcement where appropriate. This technique is simple and light, but its use is confined to the rear portion of the wing. The tissue hinge is not strong enough or tight enough to serve as the main hinge for the wing spar.

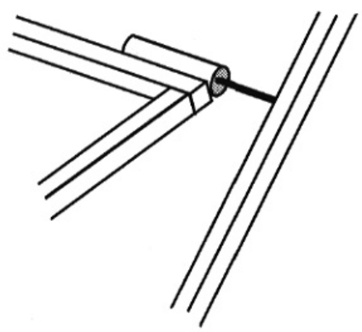
In large RC ornithopters, most of the assembly is done without glue. Wood, other than plywood, is not used extensively, and most of the parts are designed to be held together with screws. It is very useful to have a milling machine so you can make your own wing levers and other parts out of plastic or aluminum. The wing hinge construction usually consists of two ball bearings pressed into parallel plates. The plates can be made of plywood, carbon fiber, or an industrial laminate fiberglass material such as G-10. A screw, or a steel shaft, passes through the bearings and secures the wing. If the flapping mechanism operates in a plane, the connecting rod will consist of a single plate with bearings pressed into each end.

In the case of a transverse-shaft flapping mechanism, the connecting rods move in three dimensions, and therefore, ball-and-socket joints must be used. These are often referred to as ball joints, but they should not be confused with ball bearings, which have far less friction. The ball joints are sold in almost any hobby shop because they are frequently used in the control linkages of model airplanes. The ball sockets screw onto the end of a threaded steel connecting rod, and the metal balls that snap into those sockets are mounted in appropriate locations on the crank and wing lever. In most designs, each of the balls has a hole through it for a mounting screw. Otherwise, a threaded rod extends from the ball.

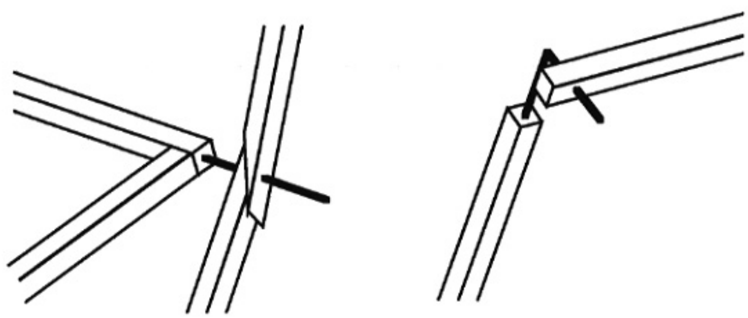
Hinge Construction for Indoor Ornithopters



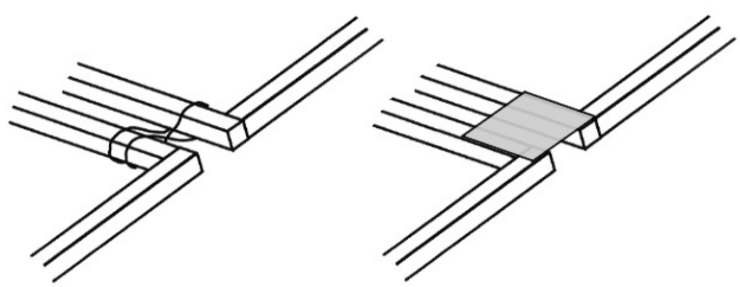
***Sheet aluminum with drilled hole.
Wire hinge pin.***



***Tube made from tissue and glue, or
from metal. Wire hinge pin.***



***Wire inserted directly through wood.
Hole area hardened with glue to form
bearing surface.***

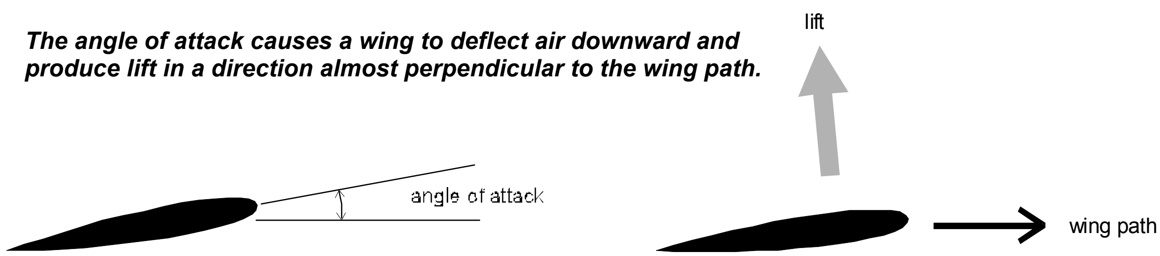


***Living hinges made from thread,
tissue, or fabric.***

Wing Design and Construction

As with the flapping mechanism, there are many ways to build an effective ornithopter wing. But there are even more ideas that don't work. Here, I'll present some of the best designs that have been proven to work. So you understand what we're trying to accomplish, I'm going to give you a quick peek at ornithopter aerodynamics. This is a rough, oversimplified version. I'll go into more detail, later in the book.

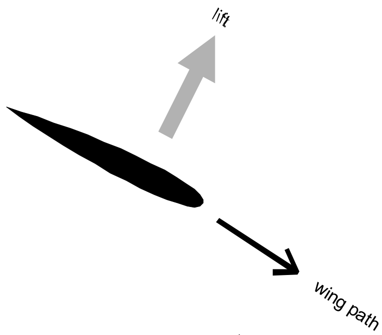
To see how an ornithopter or bird can fly, first you must understand how a simple airplane wing operates. As the wing moves forward through the air, it is held at a slight angle, called the "angle of attack". This causes the wing to deflect the air gently downward. Like when you push down on anything, there is an equal and opposite reaction force, as described by Newton's third law of motion. This is the "lift" force that keeps the airplane up in the air.



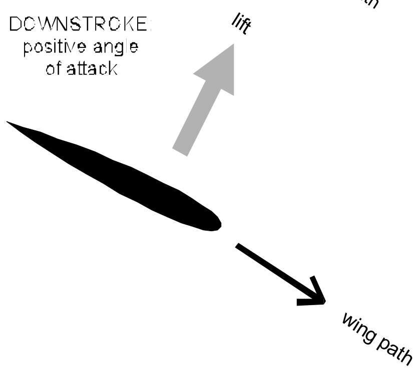
The angle of attack causes a wing to deflect air downward and produce lift in a direction almost perpendicular to the wing path.

There is some drag, or air resistance, whenever any object moves through the air. This would tend to make the airplane slow down, reducing the lift, and the airplane wouldn't be able to stay aloft. That is why an airplane needs a propeller. The propeller overcomes the air resistance and keeps the plane moving.

There is another way to solve this problem. An unpowered, glider type aircraft can maintain its speed by going into a shallow dive. The wing is angled forward so some of the lift of the wing counteracts the drag on the aircraft body. To maintain its speed, a glider must keep moving downward, relative to the surrounding air.



Glider in a dive redirects the lift force of the wing to obtain forward thrust.

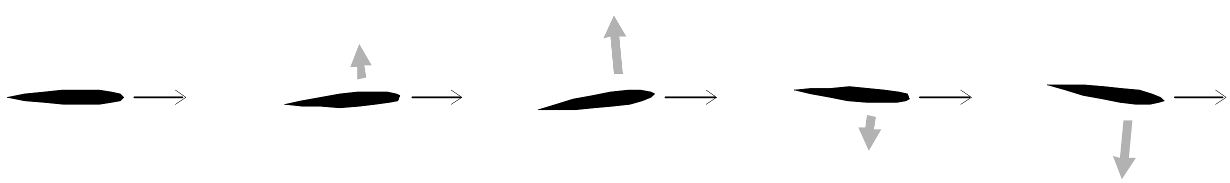


A bird's downstroke uses the same down-and-forward motion of the wing to produce lift and thrust.

The forward motion is mostly due to the forward motion of the bird's body.

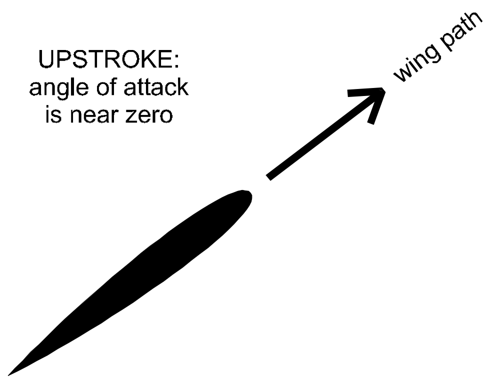
The bird or ornithopter applies power in the downstroke of the wings. The wing in downstroke works something like a glider when it goes into a dive. The downward motion and angle of the wing cause a strong lift force with a forward thrust component. Unlike a glider, only the wings are going down. The body stays up!

At this point, it's important to understand that the amount of lift and its direction (up or down) depends largely on the angle of attack. This is not the angle of the wing, but its angle *relative to the direction the wing is going*, which happens to be horizontal in the drawing below. Birds and ornithopters constantly manipulate the angle of attack in order to fly.



Varying the angle of attack controls the magnitude and direction of the lift force.

People often ask why the upstroke doesn't cancel out the downstroke. There are two reasons why. First, the part of the wing near the body has little upward motion. It acts like an airplane wing and produces lift at all times. Second, birds line up the outer part of the wing with the wing's direction of travel. In other words, the angle of attack is near zero. This allows the wing to get back in position for the next downstroke without causing too much air resistance.



During the upstroke, the outer part of a bird's wing has a very low angle of attack, so the wing passes through the air with minimal resistance.

In most ornithopter wings, the angle of attack is regulated through "aeroelasticity". This means that the wing structure deforms in response to the aerodynamic forces acting on it. Ornithopters, like birds or insects, have a stiff spar at the leading edge of the wing. The rest of the wing is flexible. The right amount of flexibility allows each part of the wing to maintain an appropriate angle of attack throughout the wing beat cycle.

There is no need to provide a greater flexibility on the upstroke, compared with the downstroke. A slight positive incidence angle at the wing root gives the inner part of the wing a positive angle of attack during the upstroke and downstroke. The root incidence also biases the outer part of the wing, so that the downstroke has a large positive angle of attack and the upstroke has a very low angle of attack.

It is possible to actively drive the twisting of the wing, instead of relying on aeroelasticity. In principle, this would allow more control over the angles of attack, perhaps resulting in more efficient flight. However, active wing twisting requires a more complex wing design and also a more complicated flapping mechanism.

Construction of Membrane Wings

The most consistently successful wing design is also the easiest to build. The wing consists of a membrane extending behind the wing spar. For support, the wing membrane can simply be attached to the body of the ornithopter, as in the Freebird. In other cases, there may be a separate "root rib", hinged to the body, which anchors the inside edge of the membrane. There is no support at the trailing edge, so the membrane can deflect upward or downward as it pushes against the air while flapping. This change in the incidence angle of the wing surface is what allows the ornithopter to fly.

The wing membrane can be made of paper, fabric, or a plastic film. For indoor models, the options include ordinary tissue paper (0.04 oz./100 sq. in.), Japanese tissue (0.03 oz./100 sq. in.), or condenser paper (0.01 to 0.02 oz./100 sq. in.). Special plastic films such as Microlite and Ultrafilm, down to 0.005 oz./100 sq.in., are made for indoor model airplanes, and these are useful for the lightest of indoor ornithopters. Outdoor models and micro-RC ornithopters may use a heavier polyester film. For the larger RC ornithopters, kite fabrics are often used.

A good technique for cutting thin membrane materials is to build a paper "sandwich" by placing two sheets of the membrane material between layers of heavier paper. Then you can cut out the membrane shape with a razor blade and have two identical wing membranes ready to glue to the frame. The sandwich technique prevents blade drag from tearing the membrane and giving a rough cut. In any case, be sure to use a fresh blade. Tissue paper can be cut with sharp scissors.

After cutting, the membrane is carefully glued onto the wing frame. A good way of doing this, which ensures the correct amount of looseness in the membrane, is as follows: First, lay out the membrane on a flat surface. It may be held in place by weighting it down with coins. Then, apply adhesive to the frame. Next, lay the wing frame down on the membrane. You can press down any wrinkles that form, but be careful not to stretch the membrane out along the spar. This would cause uneven tension that would adversely affect the shape that the membrane takes on, under load.

The type of glue will depend on the wing material. For paper coverings, you can use a non-toxic white glue, such as Elmer's Glue-All. Some builders prefer to dilute the glue as much as 1 to 10 with water, which results in a lower weight once the water evaporates. At least in heavier models, you can use the glue straight from the bottle. Plastic films do not adhere well. I have had some success with tacky craft glues, but if you want really strong adhesion, you will probably have to use something more toxic, a spray adhesive or liquid contact cement. When applying liquid adhesives to a thin carbon wing spar, apply a few drops to the spar and then wipe them along its length, between your pinched fingers, so the glue is confined to the upper surface of the spar.

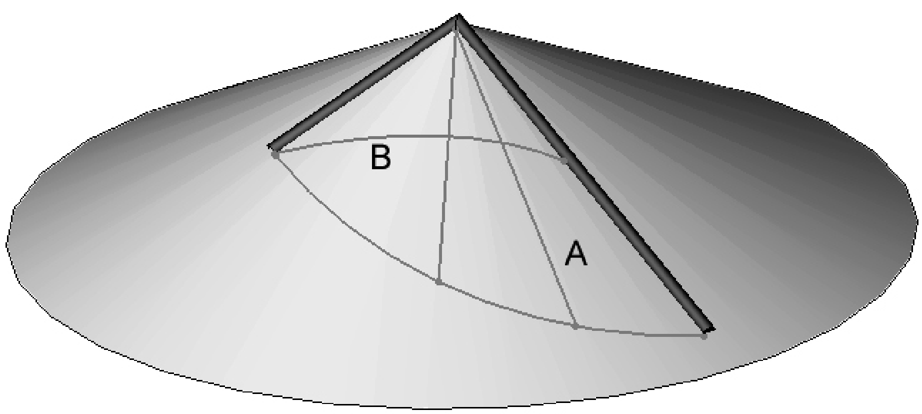
The physical properties of the wing membrane material are important. Something like Saran Wrap would be exactly the wrong thing to use, because it stretches so easily. The membrane takes on a cambered or curved shape under load. This curve allows the membrane to support a load outside the triangular boundary formed by the spar and root rib, but only if the membrane material is crisp and non-stretchy. Stretchy films require more bracing, and they are more likely to wrinkle under load. A non-stretchy plastic film such as polyester or cellophane works much better. (The "mylar" or biaxially-oriented variety of polyester film seems to fall somewhere in the middle of the spectrum and is not recommended.) The stiffening fibers in paper make it even better than plastic films in these regards. To take full benefit, the tissue grain should be aligned with the chord of the wing. Unfortunately, some tissues are permeable to air, which is not desirable.

You might be thinking, "What about bats? Don't they have stretchy wing membranes?" The bat's membrane appears stretchy, but it's actually full of muscle fibers that allow it to remain taut during flight.

Various shapes have been used for the wing outline. The choice is often dictated by aesthetics, but there are some functional considerations too. If you are using a stretchy plastic film for the membrane, you might need to use a triangular wing outline, or add battens to support the outer part of the wing. Often the wing outline is in the shape of a quarter-ellipse. The outline can also be defined by a circular arc of constant radius. You can use a computer graphics program or a little math to draw either shape. (In the back of the book, I explain how to do this.) However, there is no harm in just eyeballing a nice shape for the membrane, as long as you make sure both sides are about the same.

Notice that when you change the wing outline, you are simultaneously changing the wing area. Increasing or decreasing the wing area could have a positive or negative effect on flight performance, depending on where you are in relation to the optimal value. For that reason, the optimal wing shape could seem to vary from one model to the next. I like to use a circular arc, because it provides a generous amount of lifting area and avoids going too far beyond the outline of the frame, where the outer part of the membrane might flop over under load.

Additional battens or bracing may be added, but they are not strictly necessary. If you are going to use any battens or bracing, it is important to understand how to do this correctly. It should be noted that since the wing root and wing spar are approximately straight lines, the membrane under flapping loads will conform to the surface of a cone whose apex is located at the front, inside corner of the wing, at the base of the spar.



Under load, the wing membrane should conform to the surface of a cone. Battens (A) should radiate outward from the apex of the cone. Any other bracing rods (B) must be quite flexible so they can conform to the shape of the cone.

Radial battens help support the outer part of the wing membrane. These are indicated by the letter "A" in the diagram. They are not always necessary, because the membrane under load takes on a cambered shape that provides some support. The battens allow the membrane to extend farther out, which might be helpful in micro air vehicle competitions or in other cases where you want to increase the wing area without increasing the wingspan. The battens should always radiate outward from the front, inside corner of the wing. This allows the membrane to take on a cambered shape under load, which approximates the surface of the cone. If you put them anywhere else, they will cause improper functioning of the membrane.

Diagonal bracing (B) was introduced by Percival Spencer in order to regulate the aeroelastic twisting of the wing. If the main wing spars are too flexible, they will bend under load, causing the wing surface to deform excessively. Since the aftward bending of the spar is a major component of its deflection under load, the wing can be stiffened by adding a diagonal brace within the wing surface. However, the brace must be flexible enough to conform to the conic shape that the wing has under load. If the bracing rods are too stiff, they will cause a discontinuity in the cambered cross-section of the wing, making the airfoil less efficient.

The material selected for the battens will depend on the size and weight of the ornithopter. You might use balsa wood, bamboo, or carbon fiber rods. Indoor competitors have used very thin boron rods, but one should learn the procedures for safely cutting this material. Sharp, very small fragments can get into the skin or eyes and cause serious injury. Caution should be used with carbon materials as well. The particles cause skin irritation and possibly work their way into the body, causing chronic pain. They also pose an inhalation hazard.

Many ornithopterists are tempted to "improve" upon the basic membrane wing by placing cambered ribs along the wing. Most often, this does not improve the performance. One should keep in mind that the camber of the wing naturally reverses during the upstroke as the conical form of the wing becomes inverted. Poorly located ribs interfere with this reversal of camber. I have had good results with cambered ribs, only when the aspect ratio of the wing is fairly high, in which case you can use some cambered ribs in the inner part of the wing without interfering with the functioning of the outer part. The ribs should be somewhat flexible, in order to allow the membrane to take on a smooth shape. If the flexibility comes from using thinner rods, then the reduced weight is another advantage.

The wing spars are subject to strong bending stresses, so they must be rigid as well as light. For ornithopters weighing less than about 20 grams, and especially those with light wing loadings, balsa wood is ideal. You should be aware that balsa wood varies in density. Amazingly, one piece of balsa might be three or four times heavier than another piece the exact same size. If possible, strip both spars from the same edge of the same sheet of balsa to ensure similar stiffness and weight. Otherwise, the spars can be weighed on a precise scale to make sure they have the same weight. Relatively hard, dense balsa is typically used for wing spars. Indoor competitors have used boron or carbon to reinforce the balsa spar.

For the lightest ornithopters, balsa wood is actually better than carbon fiber. Balsa wood has a better stiffness-to-weight ratio than solid carbon fiber rods. At small diameters, the carbon rods become extremely flexible. If you reduce the diameter of a spar by half, it becomes 16 times more flexible. Therefore, carbon is not the ideal choice for very light-weight ornithopters. Balsa wood will give you a lighter, stiffer spar, resulting in better performance. The advantage is especially great if the wings are large in relation to the weight of the ornithopter. For some applications, it might be appropriate to sacrifice performance in favor of durability, in which case carbon spars would be used.

In larger ornithopters, with higher wing loadings, the impact strength becomes more of an issue than the stiffness of the spar. In such cases, carbon is preferred over wood. You can use hollow carbon rods for more stiffness and better performance, but they tend to break more easily in a crash. Therefore, solid rods are most often used.

Bamboo should also be considered. Its properties are similar to carbon fiber, at a much lower cost. Bamboo shares the flexibility and high impact strength of carbon, but you will need a thicker cross section and therefore more weight to achieve the same degree of stiffness. To insure equal strength and flexibility, the left and right spars should be stripped from the same piece of bamboo. Bamboo has one important feature not shared by carbon fiber: you can soak it in water and then bend it over the barrel of a hot soldering iron to form curves. This technique also works for balsa wood.

Tapering the wing spars is quite beneficial, as it decreases the amount of mass near the wingtips. Much energy is otherwise wasted in moving this mass up and down, in addition to the obvious effects of excessive model weight. Spars are not weakened much by tapering, since the greatest stresses are experienced in the thick, basal region of the spar. You must be careful to ensure equal thickness of the two spars. I use a razor plane, available at your local hobby shop, which allows balsa wing spars to be tapered rapidly and with a fair degree of accuracy after some practice.

Fabric Wing Construction

Larger RC ornithopters normally use some type of kite fabric for the wing membrane. Hang-Em-High Fabrics sells a half-ounce polycarbonate-coated rip-stop polyester, which is crisp, lightweight, and available in many colors. “Half-ounce” is how much a yard of fabric weighs before the coating is applied. The airtight coating greatly improves performance, and even with this coating, the fabric is still very light. You can use other kite fabrics, such as nylon, but they may not perform as well as the coated polyester fabric.

Another material you can use is tyvek. This opaque, white material gives a realistic appearance. tyvek looks like paper, but it is made of plastic fibers, so it is fairly tough and it is not damaged by water. tyvek wings can be assembled quickly with tape or white glue, and you can color the tyvek with paint or markers. tyvek is less durable than a true woven fabric, but the low cost and ease of construction make it perfect for experiments.

A good kite shop should have all the materials you need for making ornithopter wings. Some sources are listed in the back of this book. You’ll probably use solid carbon rods for the wing spars. The 1/2 oz polycarbonate-coated polyester fabric is the best wing material. A heavier dacron strip may be used to reinforce key areas. Instead of sewing, you can hold it all together with a special seam-stick adhesive. It works like double-sided tape, but when you peel the backing off, nothing is left but the adhesive itself.

First, draw half the wing outline on cardboard and cut it out. This template will ensure symmetry. You can use mathematical techniques to measure out a perfect arc or ellipse, but a smooth freehand curve will work fine. Cut out the wing fabric according to the pattern. Do not use the skewed rip-stop grid pattern of the fabric as a reference. You'll make both wings in one piece by flipping the pattern or the fabric. However, my illustrations only show one wing.

The role of carbon bracing is often misunderstood. The goal is not to divide the wing into separate regions, but rather to maintain a smooth conic surface throughout the wing. Therefore, stiffening rods should radiate outward from the front inside corner. You can secure them in place with ordinary cellophane tape, adhesive-backed fabric, or 1/2" wide strips of wing material backed with seam-stick adhesive.

The main wing spar will bend under load. We want the spar to be light, but if the wing deforms too much, we might need additional bracing to reduce the bending of the spar. This is the prominent diagonal brace, which, in Cybird and Kinkade models, snaps onto a ball joint at the trailing edge of the wing. The brace should be on the bottom of the wing for better performance. It can be permanently attached to the fabric, but it's better to put it in a sleeve, so you can experiment with different diameters. If the brace is too stiff, performance will suffer greatly.

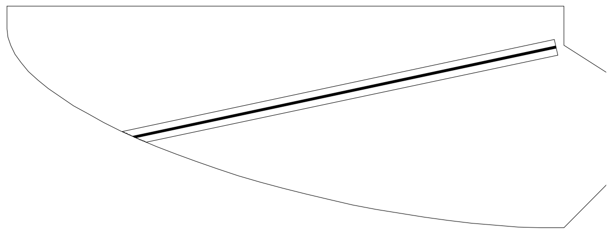
There are many other ways you can attach the trailing edge of the wing to the ornithopter body. Instead of ball joints, you can terminate each of the diagonal braces in a reinforced pocket, and simply screw the trailing edge of the wing onto the ornithopter body, using a big, nylon washer so the screw doesn't pull through the hole in the fabric.

To make the sleeve, cut a strip of dacron and crease it down the middle, lengthwise. To prevent unraveling, you can cut the dacron with a "hot knife", available from kite-making suppliers or your local hobby shop. Beware of fumes when using the hot knife. Close the sleeve, and adhere it to the wing, using seam-stick tape. Close the outer end by folding it over.

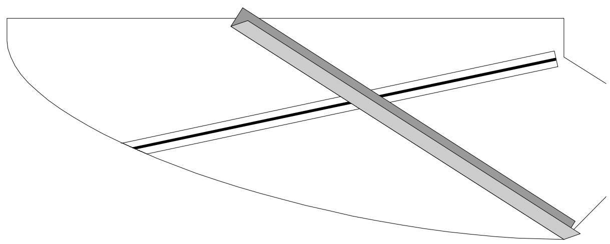
Next, reinforce edges, high stress areas, or places where the wing will attach to the body. A dacron strip down the centerline is a good idea. You can put additional fabric over the diagonal sleeve. This will hold it in place better and give it a smoother profile.

To finish the wing, apply another dacron sleeve for the main spar. Crease the dacron lengthwise and put seam-stick tape along the edges. The sleeve clamps down over the leading edge of the wing fabric, rather than sticking to only one side. Fold over the outer end and glue it in place. This forms a strong closure that should prevent the spar from poking through at the wingtip. A vinyl end cap on the wing spar also helps. The amount of tension at the left and right wingtips must be balanced for the ornithopter to fly straight. Unstick and adjust if needed.

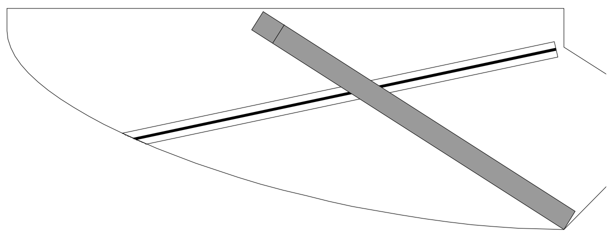
Cut out the wings.
Apply radial battens.



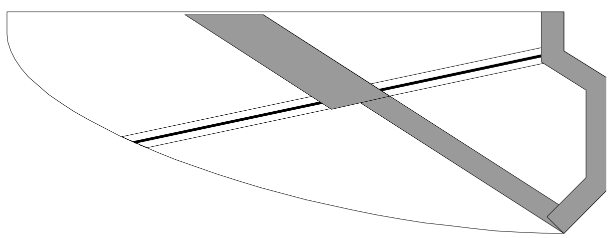
Apply diagonal brace sleeve.



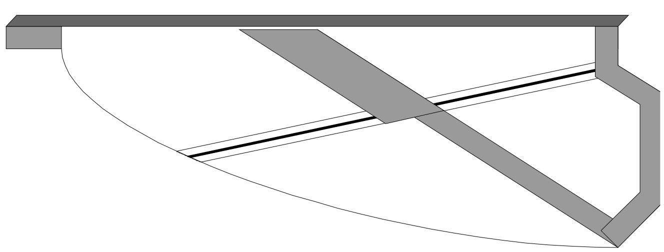
Fold over the outer end of the sleeve.



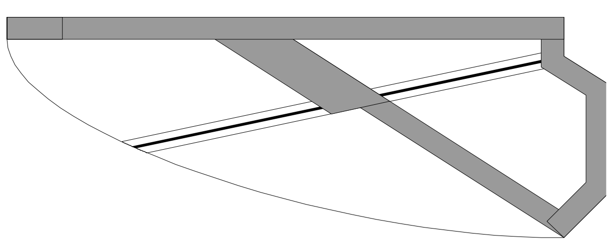
Reinforce high-stress areas.



Apply the main spar sleeve.



Fold over the tip.



Stability and Control

Getting an ornithopter to fly is only half the battle. These things are notoriously difficult to steer. Admittedly, much of the trouble arises from trying to use strange steering methods other than the tried-and-true rudder and elevator system found in many RC airplanes. But the ornithopter does have some unique characteristics you'll need to understand.

Flying Straight and Steering

For effective steering, the radio-controlled ornithopter first must be capable of flying straight. There are plenty of things that can make an ornithopter go off course, and it’s important to overcome all such difficulties. Free-flight models are supposed to go in a circle, but that circle must be carefully regulated to get the best results. In troubleshooting ornithopter trim adjustments, one must observe the flight path and model orientation carefully.

As you know, asymmetric flapping can cause the ornithopter to turn. Here are some other problems that may cause an ornithopter to turn, with possible solutions:

1. A difference in the weight of the wing spars, usually resulting from different wood densities, will cause a turn toward the heavier side. Add weight to the lighter wing spar.
2. The carbon rods used for wing spars, though straight, may bend more easily in a certain direction. It may be necessary to rotate the spars in their sockets so both sides bend equally under load.
3. If the wing membrane is tighter on one side, and looser on the other, this may cause problems. Often, the imbalance is detected as a wrinkle in the membrane of one wing, showing that it was applied incorrectly.

Whatever the cause, if the ornithopter wants to turn to one side, you can almost always correct this by adding weight to the wingtip on the outside of the turn. Through inertia, the added weight will suppress the flapping motion of the weighted wing, while increasing the flapping angle of the unweighted wing. The difference in travel range results in a difference in thrust that will compensate for any unexplained pull to one side.

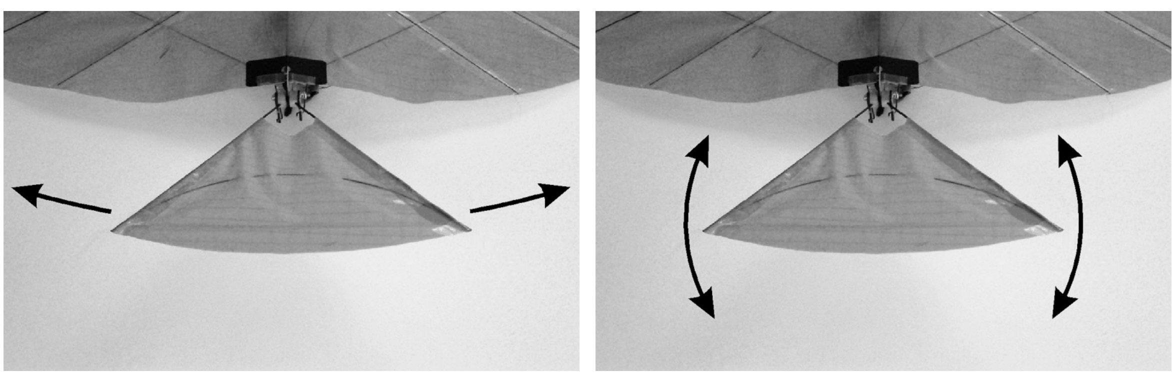
Many ornithopters lack a vertical fin or rudder, so the horizontal stabilizer is sometimes used to make a steering adjustment. This is done by rotating the stabilizer slightly about its longitudinal axis. When you do this, the stabilizer lift is directed slightly to the left or to the right, causing the model to turn. If you twist the tail boom too much, you might find that the model goes into a flat spin. Since the ornithopter makes no forward progress in this situation, it loses altitude rapidly. Reaction tandem models are especially sensitive to this problem since the whole front or back pair of wings is being adjusted.

I don’t like to use this steering method, because its effectiveness depends on the stabilizer loading. A downforce stabilizer would have the opposite effect, and if the stabilizer loading is too light, the adjustment might not be effective at all.

For rubber-powered ornithopters, the turn direction may change as the motor unwinds. This is due to the rudder (or other asymmetries in effect at low power levels) gaining more influence relative to flapping-wing effects. This is a problem for indoor flying, where a constant circle is necessary for avoiding walls. In principle, you can solve the problem by balancing the wings so that the turning at high power is minimized, and then adjusting the rudder so that the model continues to circle in the same direction as power drops off. I can usually get my ornithopters to circle with some consistency through most of the flight, but I've never matched the precision or consistency that the other guys get with their free-flight airplanes.

You can also influence the initial turning direction by how you hand-launch the model. Simply release the model with the wings banked to the right or to the left, depending on which way you want the model to go.

For radio-controlled ornithopters, steering is usually done by the tail. The wings can be used for steering, but this is less consistently successful and more difficult to implement. A simple elevator and rudder system is usually effective for ornithopter steering, as long as the wings are properly balanced. For a more birdlike appearance, a flat, fan-shaped tail is more often used. For steering, the tail may swing out to the left and right sides, so that the downforce of the tail causes a rolling moment on the ornithopter. Alternatively, the tail may rotate about its long axis. In this case, the downforce is redirected in a way that provides yaw control. In some RC ornithopters, the tail rotates about an oblique axis, combining the two motions described here.



Alternate methods of steering include a swinging or tilting motion of the tail.

A great many RC ornithopters are reluctant to come out of a turn. In the worst cases, the steering system will not provide enough control authority to break out of the turn. In any case, the locking tendency should be minimized, because even if you are able to break out, it prevents the model from tracking straight and delays the steering response. It is important to differentiate between this locking-in phenomenon, where the ornithopter will continue to turn either left or right, depending on the initial conditions, and the previously-described tendency to turn in a particular direction. If the ornithopter wants to turn in a particular direction, you can correct that by weighting the wingtip. But if the ornithopter is locking into any turn, in either direction, then you need a different solution. Locking in is caused by too little dihedral or having the center of gravity too far forward. If the ornithopter already has plenty of dihedral and still locks into a turn, you can move the center of gravity to the rear and then adjust the elevator trim as needed. The typical forward sweep of ornithopter wings may contribute to this problem.

Too little dihedral often causes another, more spectacular, sort of failure. In this case, the model climbs upward a few meters or so but then banks tightly and spirals to the ground. This could also be caused by a difference in construction between the left and right wings.

Pitch Stability

Stability in pitch determines whether your ornithopter will nose dive or go through a series of stalls. In many cases, you can overcome these problems just by adjusting the angle of the tail up or down. Notice that when you *raise* the tail, it has a *negative* incidence angle, relative to the wing root. Therefore, "negative stabilizer" means raising the tail. Here are some common situations and how to fix them:

1. If the ornithopter goes through a series of stall-dives before striking the ground nose-first, this is caused by too much negative stabilizer. You might try to correct this problem, only to find that the model then nose-dives. If you can't make the ornithopter stable by adjusting the stabilizer angle, then you probably have to increase the stabilizer area or tail boom length.

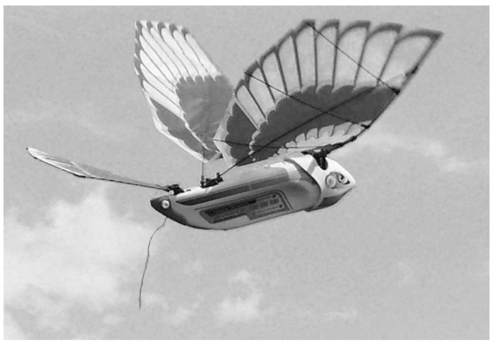
2. Sometimes, the ornithopter flaps vigorously but sinks slowly to the ground with little forward progress. This "mushing" behavior results in the tail striking the ground first and is often caused by a far aft center of gravity or too little stabilizer area. This often happens only after the power has been mostly expended.

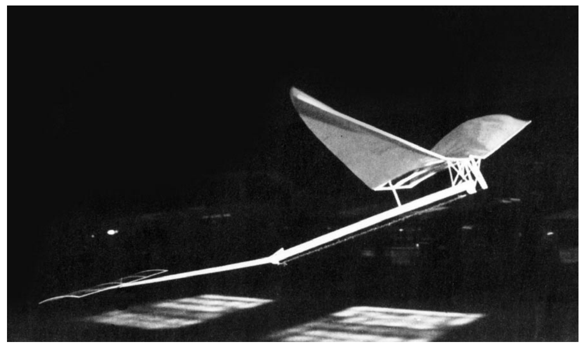
3. In some cases, the ornithopter makes a rapid dive straight to the ground or tumbles head-first. This is usually caused by not enough negative stabilizer angle, or not enough stabilizer area. If you manage to get the center of gravity too far forward, that could do it too.

Of course, if the stabilizer is in the front, then the stabilizer incidence is positive. You would increase the angle to prevent a nose dive or decrease the angle to prevent a stall.

In adjusting the center of gravity location, it is better to remove weight from one end of the model than add it to the other end. This may mean rebuilding part of the model in lighter wood. Making the stabilizer bigger is also a good substitute for adding weight at the opposite end of the model. Some extra lifting surface in the rear allows your ornithopter to tolerate a farther-back center of gravity location.

There is one important difference in stabilizer function between airplanes and ornithopters. In airplanes, the stabilizer usually provides lift. In many ornithopters, however, the tail produces a strong downforce. This is in order to compensate for a nose-diving tendency that many ornithopters have. Because the tail produces a downforce, the incidence angle is more negative than a typical airplane stabilizer. The angle is typically about negative 15 degrees, relative to the wing root, but it may be less, or more, depending on where the center of gravity is located, and other aspects of the ornithopter design.





In this commercially-produced RC model, Cybird P1, the stabilizer produces downforce, whereas in Roy White's design, Rara Avis, the stabilizer produces lift.

In certain rubber-powered ornithopters, the motor stick has been elongated in an effort to increase duration. Since the center of gravity is farther to the rear, the stabilizer provides lift instead of downforce, and the incidence is only slightly negative, more like an airplane. Obviously, the lifting stabilizer is more efficient, and this is what birds use. Unfortunately, the farther-aft center of gravity location can decrease the directional stability of the ornithopter. Real birds are actively stabilized by their nervous systems, but your ornithopter might need a vertical fin to prevent it from going into a spin and keep it tracking straight.

If the stabilizer is in front, it will always produce lift, and so it will always have the normal amount of incidence.

In airplanes, the center of gravity is usually located near the center of lift of the main wings. For rubber-powered ornithopters, this is not always possible. Without using some kind of heavy and complicated mechanism, the wings cannot be placed mid-fuselage as in airplanes. Instead, the flapping mechanism and wing spars must be located at the front or back end of the rubber motor. Indoor competition models, with their need for long flight times, have long motor sticks that extend quite far from the mechanism and wing spars. In the case of rear-stabilizer models, this places the center of gravity far behind the trailing edge of the wings. Likewise, if the stabilizer is in front, then the motor stick extends forward from the flapping mechanism, placing the center of gravity far ahead of the wings. In either case, the stabilizer must carry a large portion of the model's weight.

Only under limited circumstances is it possible to keep the center of gravity close to the center of lift of the flapping wings. This occurs only in the rear-stabilizer design, and then only if the motor stick is fairly short, its length roughly equaling the root chord of the wings. Of course, with electric power, you have far more control over the center of gravity, since you can place the battery and radio components where you wish. In such models, the center of gravity is usually about one third of the way back from the leading edge of the wing.

As mentioned earlier, ornithopters often have a tendency to pitch downward or nose-dive. The ornithopter may need a far-aft center of gravity location or a lot of negative stabilizer to compensate for this tendency. The problem results from the high thrust line of the flapping wings. Since the wings are usually attached at the top of the ornithopter, and are raised farther by their average dihedral angle, any thrust produced by the wings is directed along a line that is well above the ornithopter's center of gravity. The high thrust line tends to exert a negative pitching moment on the ornithopter.

The high thrust line causes the ornithopter to behave differently, depending on the amount of power. As the power drops off, the nose-down tendency becomes weaker. Therefore, rubber-powered ornithopters often tend to nose-dive with a fully-wound motor, but tend to go through a series of stalls toward the end of the flight. Electric ornithopters are similarly effected by changes in the throttle. A larger stabilizer seems to alleviate power-dependent stability problems. You can also try raising the center of gravity, by positioning the motor stick or electrical components higher on the model. However, it is possible for the center of gravity to be too high, in which case the ornithopter will stall under power.

The power level will also affect the load on the stabilizer. It could go from negative to positive within the same flight. This in turn could affect the steering of the ornithopter, or its ability to circle consistently in the case of a free-flight model. By moving the center of gravity fore or aft, you can give the stabilizer a more consistent load.

When the flapping stops altogether, the ornithopter's behavior changes markedly. The typical membrane-winged ornithopter glides very poorly. With the wings stopped, the wing membrane takes on the same conical shape it has during the downstroke. This shape is better suited to the downstroke than it is to gliding flight. To make matters worse, the force of lift on the wings usually pushes them up into a "V" position. With this high dihedral angle, the wings cannot produce much lift, so the ornithopter drops rapidly. This "V" configuration also tends to be unstable, resulting in a spin. On some flights, the wings may stop at the extreme anhedral or lowermost position, also resulting in a loss of stability.

On the other hand, some ornithopters glide fairly well. With a little luck, the last bit of torque in the rubber motor may balance the force of lift on the wings, thus keeping the wings at a suitable dihedral angle for gliding. Without relying on that phenomenon, or some type of wing-leveling device, the tendency to destabilize in the glide can be reduced by limiting the flapping amplitude, thereby making the extreme wing positions less extreme. Biplane ornithopters tend to glide better than monoplanes, because the wings are not driven into an extreme position by the force of lift. At least two of the wings will usually be in a good position for gliding.

With membrane wings, the amount of tension or slack in the membrane has a great effect on performance. The optimal amount of tension is different for each ornithopter, and you can approach that value through experimentation. Typically, I construct wings so that the membrane has no tension or slack when applied to the frame. If the spars are quite flexible, or if the aspect ratio is unusually high, it may be advantageous to build some tension into the wings. The springy spars are bent back slightly, so they maintain some evenly distributed tension on the wing membrane. This reduces the amount of deformation under load, so it is like increasing the pitch of a propeller. It increases the top speed of the ornithopter.

With increased tension, you will likely have to move the center of gravity forward. If the wings are too slack, the ornithopter will tend to nose dive, and you must move the center of gravity substantially to the rear to compensate for this. The slackened membrane tends to perform poorly overall, but it might be helpful in achieving slower flight speeds.

Sizing the Rubber Band

The characteristic indoor ornithopter flight begins with a tight spiral climb under high power, which then levels off into broad circles and ends in a gradual, flapping descent. If the model is properly trimmed and has the right size rubber band, the wings should stop flapping about when the model reaches the ground. No one likes to see an ornithopter land under power, with wings beating furiously against the ground. This situation is distressing to the builder and often damaging to the machine.

The amount of climb is a critical factor for indoor models, because reaching the ceiling can be disastrous. The Academy of Model Aeronautics (AMA), which regulates model airplane competitions in the United States, classifies ceiling heights into four categories and maintains separate records for each category. Category I indicates a height of 8 meters or less, II indicates 15 meters or less, and III indicates 30 meters or less. Category IV is anything higher than 30 meters. The height reached by an ornithopter can be regulated, with practice, by adjusting the length and thickness of the rubber motor. Short, thick motors provide a steeper climb and shorter duration than long, thin motors of the same weight. Predictably, high ceilings allow longer flight times than low ceilings.

For the best possible flight times, indoor model competitors often use a rubber band that is somewhat longer than the distance between motor hooks. They use a special winding device, which allows them to stretch the rubber band, wind it up while slowly walking the winder toward the model, and then put the rubber band onto the motor hook. Winding can be done off the model or with one end of the rubber band still hooked on. The model may be held by an assistant or mounted on a stationary support called a stooge. Threading the rubber band through a small rubber o-ring makes it much easier to get off the winder and onto the model.

The longer rubber band can hold far more turns, potentially making the flight times longer. However, this must be balanced against the added weight. Through experimentation, you can get an idea of the best length and thickness of rubber, given the height of the ceiling. A typical motor length might be 1.5 to 2 times the distance between motor hooks.

Indoor flyers have a special technique for making test flights under low ceilings. Instead of using the full rubber band motor, they often use one that is half or one-fourth as long. It is necessary to shorten the distance between motor hooks accordingly. This is accomplished using a length of steel music wire with hooks on each end. The wire should be the same weight per inch as the wound-up rubber band. When using a half motor, your model should fly half as long and go half as high as with a full motor. This allows you to make better predictions about how your model will perform under a high ceiling than simply winding it up part way. Consult with some of the excellent books on indoor model airplane flying to learn some more techniques.

If you are flying outdoors, you can adjust your model for maximum climb in the hope of catching a thermal. If you manage this, the ornithopter will remain aloft long after the flapping has stopped, and you may have the pleasure of watching it get smaller and smaller until it disappears forever into the clear blue sky.

Body Design

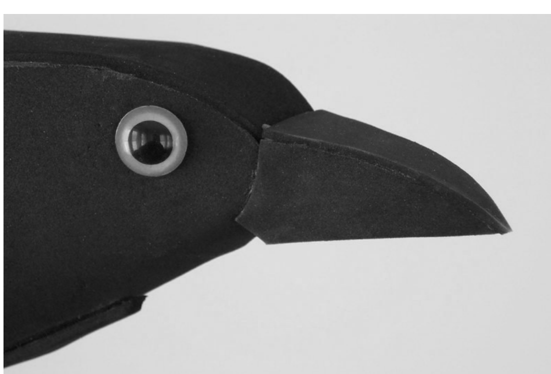
RC ornithopter bodies usually consist of a flat plate, with holes cut into it for the servos, battery, and other components. Typically the body plate is made from aircraft plywood or a fiberglass or industrial laminate material such as G-10. Plywood is lighter, easier to work with, and easier to repair, although it is less resistant to impact. The plywood can be cut to any desired shape using a scroll saw. In very small and lightweight ornithopters, a more open framework is often used. All these types of ornithopters are easy to build, but they don't look nice, and they certainly don't look like a real bird.

The solution is to cover the body in some kind of outer shell. This was done with many of the mass-produced toy RC ornithopters. If you carefully remove the body, you can see the open framework or flat plate structure underneath.

You can improve the realism of your own RC ornithopters using craft foam. This material is easy to use, inexpensive, and fairly durable. It comes in a wide variety of colors, and it can be decorated with permanent markers. Foam bodies or heads can be attached to the frame using velcro. You might have trouble getting the adhesive backing of the velcro to stick to the frame of the ornithopter. One solution is to secure it in place with a strong thread. In the example shown, I used some extra foam to reinforce the seam along the bottom of the head. For an even more realistic appearance, some people have made their own hollow fiberglass bodies.

The finishing touch is a set of eyes. These are available at craft stores, and they mount easily in the foam. You can paint the back of the eye with enamel paint so it matches the color scheme of your ornithopter. Pre-painted eyes are also available.

It's a good idea to study pictures of real birds when planning your ornithopter body. Otherwise, you'll realize too late that it doesn't have the right proportions and doesn't look like a real bird. Adding a touch of realism with these three-dimensional body shells can help make a big impression on spectators, and it might even get more of a reaction from real birds!



IV. Aerodynamics

It hasn't been necessary to say much about ornithopter aerodynamics up to this point, because the tried-and-true membrane wing design will always perform well, even if you don't understand it. Since you may be interested in developing your own wing designs, it may at some point be necessary to understand what's really happening when an ornithopter or bird flies.

Most flying objects, whether airplanes, birds, or ornithopters, use airfoils to produce the lift and thrust necessary for flight. An airfoil is any part or surface of the flying object that produces a force as a result of its motion relative to the air. This includes wings, fins, propeller blades, rudders, etc. They all work basically the same way: by deflecting the air as they pass through it. In other words, by accelerating the air mass, by changing its velocity. There are some common misconceptions about how an airfoil works, and we must overcome those before moving on.

Understanding Airfoils

The airfoil is an example of an inclined plane. In operation, it is something like a wedge or ramp, in that it allows a larger force to be produced, as a result of a smaller input force. You can't get something for nothing. The larger force acts over a shorter distance. But when it comes to supporting the weight of an aircraft, the amount of force is mostly what matters.

The word "airplane" derives from the fact that a wing is a type of inclined plane. A propeller-driven airplane uses two sets of inclined planes to increase the force of the engine. First, the propeller converts the engine torque into a forward thrust. Second, the forward thrust drives the wings through the air, allowing them to produce a vertical lift force that can be many times greater than the thrust from the propeller. This simple method for the amplification of force probably explains why airplanes flew before ornithopters. In ornithopters, a gear reduction takes the place of the first inclined plane force amplification, carried out by the propeller.

Since airfoils operate in a fluid medium, they are a little different from a ramp or wedge. The fluid, air, consists of randomly moving particles called "air molecules". (They are mostly nitrogen and oxygen molecules, N_2 and O_2.) Each molecule has positively charged nuclei inside and a negatively charged electron "cloud" around the outside. From a distance, the positive and negative charges cancel out. However, when two molecules come very close together, the negative charges cause the two molecules to strongly repel each other. We can think of them as colliding and bouncing off each other, even though at the atomic level, nothing actually touches anything else. In the same way, air molecules will bounce off of solid surfaces, like a wing.

For our purposes, it doesn't matter whether the air or the airfoil is moving. Often, explanations of aerodynamics pretend like the air is moving around a stationary wing. This is completely valid, and it makes intuitive sense if you are onboard the aircraft. However, I will use a different frame of reference. In the following discussion, the air mass is stationary, and the airfoil moves through it. Let's say we have an airplane wing, moving horizontally through the air. The wing is inclined slightly so that it can deflect the air downward as it passes through.

As the leading edge of the wing comes into view, it divides the air mass. Some air molecules are above the wing, and others are below it. Air molecules below the wing will tend to collide with the lower surface of the wing and get pushed out of the way, downward. The increased frequency and speed of the collisions constitutes an increase in air pressure, exerting an upward force against the bottom surface of the wing.

On the top of the wing, something opposite happens. As the wing moves forward, the downward sloping wing surface retreats from the air mass, causing a reduced frequency and velocity of collisions, or a decrease in air pressure. Collisions among air molecules cause some of the air molecules above the wing to move downward and partially fill the vacuum. Both above and below the wing, the air mass is shifted downward.

The total lift force acting on the wing is equal to the pressure gradient: the difference between the air pressure above the wing and below the wing. The lift force is also directly related to the velocity and mass of the air deflected downwards. Newton's third law of motion states that for every action, there is an equal and opposite reaction. As applied here, the force exerted downward against the air mass is equal to the upward force on the aircraft.

At the same time, the force exerted forward against the air mass, which causes a forward displacement of the air, is equal to the drag force on the aircraft. Airfoils typically have a smooth shape with a rounded leading edge and tapered trailing edge, because this shape allows the air to be deflected downward with a minimum of drag.

If the wingspan is large, as in a sailplane, then the velocity with which air is deflected downward will be low. If the wingspan is small, then the air must be deflected downward with a greater velocity in order to produce the same amount of lift. The latter strategy requires more energy to produce the same amount of lift, but the extra energy expenditure gives you a higher flying speed, which might be useful in certain applications.

Bernoulli's Principle

There is a *false* explanation of how airfoils produce lift, which is often given in the literature. It goes something like this. Air flowing above the wing has a greater distance to travel, because it must follow a curved surface. Therefore, the airflow above the wing speeds up. Bernoulli's principle shows that as the velocity increases, the pressure decreases. This supposedly causes the pressure gradient that we think of as lift.

There are several problems with this explanation. First, not all airfoils have a cambered upper surface and flat lower surface. A symmetrical airfoil works just fine. In fact, planes can even fly upside-down! Second, the idea that air molecules speed up just because they have farther to go is nonsense. The air molecules above the wing don't really keep pace with their counterparts below the wing. They do speed up, but there is a real physical mechanism for this, which is the fact that there is already a void left behind the wing as it moves through the air. Air accelerates into the space above the wing. The higher flow velocity above the wing is caused by the pressure gradient – not the other way around.

Bernoulli's principle states that a fluid, such as air, exerts less pressure when it is moving. If the air molecules are tending to move in a particular direction, relative to the wing, then they are less likely to collide with the wing, and when they do collide with the wing, the velocity perpendicular to the surface is likely to be lower. This effect contributes to the pressure gradient we discussed earlier. Bernoulli's principle is a sound concept, but it cannot stand alone as an explanation of how wings produce lift.

Angle of Attack

The force produced by an airfoil largely depends upon the angle it is held at when it passes through the air. This angle between the wing surface and the wing's direction of travel is called the "angle of attack". At zero angle of attack (or a small negative angle if the airfoil is cambered) the airfoil simply passes through the air, without deflecting it up or down. There is a small amount of air resistance or drag, but no lift is produced. If the angle of attack is positive, the wing will deflect air downward, producing lift. If the angle of attack is negative, the wing produces a downward force, the opposite of lift.

In the following paragraphs, lift is defined as the force acting perpendicular to the travel of the airfoil, and drag is defined as the force acting against the travel of the airfoil. Elsewhere in this book, I have sometimes used the word "lift" to refer to the overall combined force, otherwise known as the vector sum of lift and drag, or the "resultant" force.

If the airfoil has a cambered shape, that affects its behavior. If the airfoil has a symmetrical cross-section, it will produce the same amount of lift or downforce, and the same amount of drag, regardless of whether the angle of attack is positive or negative. If the airfoil has a cambered or asymmetric cross-section, it produces more lift at positive angles of attack, whereas it produces less lift and more drag at negative angles of attack. In other words, the lift over drag or "L/D" ratio is better if the angle of attack is positive. In general, a thick airfoil with a rounded leading edge offers a good L/D ratio over a wide range of angles of attack. A thin plate-like airfoil offers a good L/D ratio within a narrower range of angles of attack.

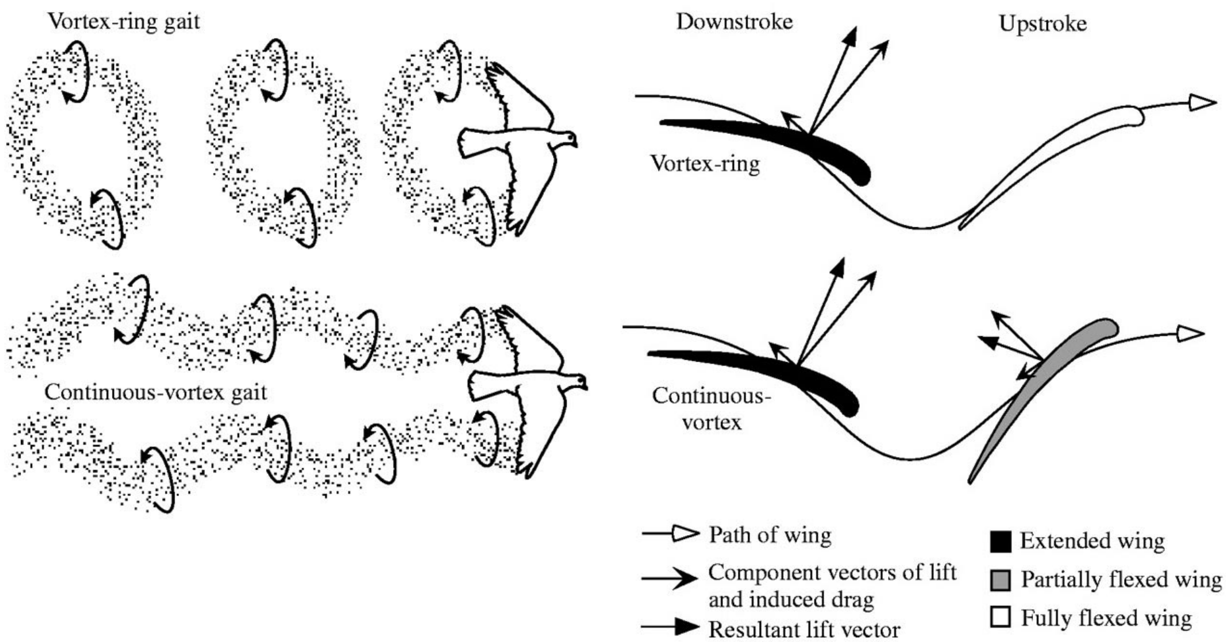
As the angle of attack increases, the amount of drag increases. At some point, the airflow above the wing becomes turbulent, resulting in a sudden increase in air resistance and decrease in lift. This is referred to as a "stall". The "coefficient of lift" is a number expressing the relative amount of lift that is produced at a given angle of attack. The coefficient of lift increases with increasing angle of attack, up to the point of stall, and then it decreases. Finally, at an angle of attack equal to 90 degrees, the wing produces a large amount of drag and no lift at all.

So far, it was assumed that the airfoil would have a constant horizontal motion through the air. However, the airfoil could just as easily travel at some other angle. The force produced by an airfoil is relative to its path through the air. For example, imagine an airplane flying horizontally, with its wings producing a vertical lift force. If the airplane goes into a dive of, let's say, 30 degrees, then the wing path is declined 30 degrees downward. Assuming that the angle of attack is not changed, the lift force also is rotated forward by the same 30 degrees. As a result, there is less force acting against gravity, so the airplane accelerates downward. At the same time, some of the lift force is helping propel the airplane forward, so its horizontal speed increases.

With airplanes, the goal is usually to keep the wings at some optimal angle of attack, something like 5 degrees maybe, so they can continue to produce a steady lifting force. With ornithopters, we must manipulate the angle of attack constantly.

Vortex Theory of Lift

When air is deflected downward, it cannot continue going straight down, because the space is already occupied by air. Therefore, air tends to circulate in a vortex. Airplanes throw a continuous spiral vortex from each wingtip. Birds and ornithopters throw off a large vortex with each downstroke. During the upstroke, the vortex is interrupted or contracts. The force required to produce the vortex is lift, and the energy contained in the vortex equals the power required for flight. Eventually, the rotational energy of the vortex is converted to heat, due to friction with the surrounding air.



Vortex formation in bird flight. The vortex-ring gait is used in slow or hovering flight. The continuous-vortex gait is used in rapid flight. Hedrick, T. L., B. W. Tobalske, and A. A. Biewener. 2002. Estimates of circulation and gait change based on a three-dimensional kinematic analysis of flight in cockatiels (Nymphicus hollandicus) and ringed turtle-doves (Streptopelia risoria). Journal of Experimental Biology 205:1389-1409.

You might read about "leading edge vortices", which are something different from the main vortices involved with lift and propulsion. A leading edge vortex forms along the upper surface of the wing's leading edge, just before the wing stalls. Ornithopters may develop leading edge vortices during the downstroke, and the brevity of the downstroke may prevent a full stall from developing. This allows the wings to operate at a higher coefficient of lift than would be possible, or safe, in a fixed-wing aircraft.

How Ornithopters Fly

Because ornithopter aerodynamics is a complex topic, we will begin by considering the simplest type of ornithopter: those in which, like airplanes, the lift and thrust are produced by separate surfaces. As mentioned earlier, the extent to which an ornithopter uses fixed surfaces for lift varies along a continuum, but this section will consider the ideal case, in which the flapping wings provide no lift at all.

Flapping Propellers

In the ideal fixed-lift system, the flappers can be regarded as a propeller that cyclically reverses its direction, pitch, and camber. Whereas each blade of a rotating propeller continues round and round, each blade of a flapping propeller traverses a certain angle and then reverses direction, twice per cycle. If the typical membrane structure is used, the membrane pitch and camber will reverse automatically as the airfoil changes its path through the air. The forces produced in the upstroke and downstroke are the same, but opposite to one another.

Aerodynamically, there is one major difference between a flapping propeller and a rotating one. Since the blades of a propeller spin continuously in one direction, they produce torque, which tends to rotate the craft about its longitudinal axis. The flapping propeller, in contrast, has two blades rotating in opposite directions. Rather than producing torque, this arrangement produces an alternating up-and-down force on the aircraft, resulting from the alternating downstroke lift and upstroke negative lift of the flapping blades. The vibration can be eliminated using a second set of blades whose motion is opposite that of the first set. The net force produced is thrust.

The term “advance ratio” describes how far an aircraft moves forward with each rotation of the propeller, or with each cycle of the flapping wings. (It is a ratio because the forward travel is divided by the distance the blade tip travels along its arc.) In order to maintain a suitable angle of attack, the blade angle *relative to the aircraft* should be adjusted according to the advance ratio: For rapid flight, the blades are angled slightly from the travel direction of the aircraft, whereas for slow flight, the blades are angled almost perpendicular to the travel direction of the aircraft. In this way, a propeller can be set up to operate at either a high or low advance ratio.

To complicate matters, the inner part of the propeller requires a different angle than the outer part. Therefore, we don’t use degrees to measure the blade angle. Instead, we consider the distance that the propeller is designed to go with each rotation. This distance is the propeller “pitch”. (Technically, this is the distance that the propeller would go, if it could maintain a zero angle of attack. In normal operation, the angle of attack is slightly positive.)

For ornithopters, the word “pitch” has often been used to refer to the actual angle of the wing surface, relative to the long axis of the ornithopter body. A positive angle indicates that the leading edge is higher than the trailing edge (as in the upstroke), whereas a negative angle indicates that the leading edge is suppressed (as in the downstroke). By this definition, the pitch is said to vary along the span, whereas the pitch of a rotary propeller applies to the whole. Notice also that the two definitions give opposite results: a rotary propeller with a high pitch would be best for rapid flight (high advance ratio), whereas a flapping wing with a high pitch is best for slow flight (low advance ratio). To avoid confusion, I have used the word “incidence” instead of “pitch” when describing the wing angle relative to the longitudinal axis of the ornithopter. This allows the word “pitch” to retain the same meaning that it has for rotary propellers.

Lift from Membrane Wings

To get our flapping propeller to start producing lift, all we have to do is angle it up a bit. Without any change to the wings themselves, they start producing lift as soon as there is some positive angle between the wing root and the flight path of the ornithopter. This increases the overall incidence angle of the wing, so that any given part of the wing has a more-positive angle in the upstroke and a less-negative angle in the downstroke.

It is intuitively obvious that a positive incidence angle should result in lift, but let us examine precisely why this is so. For simplicity, I will initially ignore the fact that the inner part of the wing operates differently from the outer part. The spanwise gradation of lift and thrust forces will be explained later in this chapter.

There is a common misconception about how ornithopters produce lift. This is called the “vectored thrust” model. In the flapping propeller, if you average the upstroke and downstroke, the overall force is a thrust which acts parallel to the wing hinge line. According to the vectored thrust model, the same is true for flapping wings that are producing lift. All lift results simply from redirecting the thrust force that acts parallel to the hinge line.

If you've ever seen an ornithopter in flight, you might be concerned about one of the predictions of the vectored-thrust model. Specifically, the model implies that an ornithopter's wing hinge line should be inclined enough for thrust vectoring to support the aircraft weight. Since weight is normally much greater than drag, the hinge line should be almost straight up! Observably, ornithopters fly with hinge line angles around 15 degrees, suggesting that there is far more lift at a given hinge line angle than the model predicts. Moreover, the static thrust produced by ornithopters is usually somewhat less than the weight of the ornithopter. In order for an ornithopter to fly at a hinge line angle of even so low as 30 degrees, the static thrust would have to be twice the weight of the aircraft!

The vectored thrust model ignores one important fact: Ornithopter wings produce additional lift as a result of their forward motion through the air, and by manipulating the angle of attack. By manipulating the angle of attack, we can have the downstroke produce a large lift force, yet prevent the upstroke from producing a comparable downforce. The part of the wing near the body of the ornithopter has little up-and-down motion, and it works much like an airplane wing. It produces lift all the time, just by its forward motion through the air. With the common membrane wing design, you get both benefits simply by setting the wing root at a slight positive incidence. No change of wing design is necessary.

Spanwise Variation in Lift and Thrust Forces

A propeller, whether it flaps or rotates, has different forces acting near the ends of the blades than near the center. The relative airflow near the center comes from almost directly ahead of the aircraft, while the relative flow near the blade tips is due mainly to their rotation or flapping. The direction of the forces produced at any point on the blade span is therefore determined by the distance from the center of rotation.

The inner portion of a flapping wing behaves much like a fixed airplane wing, because it has very little up and down motion. This part of the wing does not produce much thrust. However, it can produce a lot of lift due to its forward motion through the air. To get from flapping propeller to lift-producing wing, no change in wing design is necessary: All we have to do is supply the necessary positive incidence.

The outer portion of the wing has a somewhat different function, because the up-and-down flapping motion is superimposed onto the forward motion of the ornithopter body. This gives you a down-and-forward wing path in the downstroke and an up-and-forward wing path in the upstroke. For the downstroke, the wing can operate at a fairly high angle of attack, producing a strong lift and thrust force. We can visualize the downstroke resultant (the vector sum of lift and thrust) gradually tilting forward as we progress from root to tip.

The upstroke resultant can be imagined to rotate from near vertical at the wing root, gradually tilting backward as the wing path becomes more steeply inclined. This would cause the outer part of the wing to produce a large amount of drag. However, this is prevented by operating the outer part of the wing at a low angle of attack. Therefore, the magnitude of the resultant decreases as we move farther out the wing.

In very slow or hovering flight, the outer part of the wing may even operate at a negative angle of attack in the upstroke. Given the up-and-forward wing path, this would produce a down-and-forward resultant, which is not particularly helpful. However, if the flapping axis is tipped backward, so that the wing path is near horizontal, then the resultant can be oriented almost straight up. The figure-eight flapping that hummingbirds use when hovering allows both the upstroke and the downstroke to produce a vertical resultant force. This is more efficient than a helicopter, because the helicopter's resultant includes a torque component, which must be compensated for.

Although it may seem impossible to optimize the angles of attack along the wingspan, throughout the upstroke and downstroke, the simple membrane wing design achieves the necessary angles automatically. This likely accounts for its widespread use. The geometry of the membrane wing under load is not perfectly matched to the wing path, but it is close enough to give consistently good performance. This is like the airplane propeller, in which a simple screw shape gives a nearly optimal design.

The standard membrane wing can be modified, in order to tweak the angles of attack in different areas of the wingspan. Usually, when there is no load on the wing surface, it returns to a mid-position that is in-line with the wing root. (Even the weight of the wing material is enough to deflect it from this relaxed mid-position.) You can change the mid-position or neutral incidence by giving the spar a slight downward curve. This gives the outer part of the wing a higher midpoint incidence than the wing root. As a result, the outer-wing upstroke and downstroke both have a higher incidence than before. This would result in less thrust in the downstroke and more lift in the upstroke. The ornithopter tends to fly more slowly but needs more power to fly.

You can also change the wing hinge line, relative to the wing root incidence. Structurally, this requires a separate piece for the wing root. It will not work if the wing is rooted in the ornithopter body. I'm not sure what the effects of this would be. Larry Burks first presented this idea to me, many years ago. He changed the root incidence without changing the hinge line angle, which is not the same as just changing the hinge line angle by itself. It seems like a good area for some new experimentation.

An interesting problem occurs in rubber-powered monoplane ornithopters. Since the rubber band exerts a constant torque on the crank, the upstroke tends to proceed much more quickly than the downstroke. At the start of the upstroke, the wings accelerate until the aerodynamic resistance to flapping fully opposes the motor torque. The resistance to flapping unfortunately consists of a strong negative lift or downforce generated in the outer part of the wing, which is accompanied by a very steeply inclined upstroke wing path.

To solve this problem, various methods have been tried, such as adding a spring to assist the downstroke, or using a special mechanism which gives the downstroke more torque than the upstroke. Perhaps the best solution is to use four wings. In biplanes, the motor torque is held in check not by negative lift, but by the positive lift of the concurrently downstroking wings.

For typical monoplanes, the upstroke wing torque will be opposite to the downstroke wing torque and roughly equal in magnitude. This would seem to suggest a large net downforce for the upstroke. However, the outer part of the wing has a much greater influence on torque than the inner part. (Specifically, the sum of the resistance to flapping, times distance from the hinge, for all points along the wing is equal and opposite the torque imparted to the wing by the flapping mechanism. Resistance to flapping includes friction and inertial components as well as the aerodynamic resistance.) Therefore, the lift in the inner part of the wing can potentially exceed the outer wing downforce, even though there is a large negative torque as dictated by the rubber band. Through aeroelasticity, the negative lift in the outer part of the wing increases the incidence of the whole wing, and that facilitates lift production in the inner part of the wing.

Temporal Variation in Lift and Thrust Forces

The previous section provides a fairly complete understanding of the mid upstroke and downstroke, but it will be useful to consider the rest of the flapping cycle: specifically, the reversal between strokes that occurs twice in each flapping cycle.

We have already discussed the dead-center effect, in which the crank is briefly unloaded at the end of each stroke and jumps forward suddenly. While this is occurring, the membrane must reverse its pitch, and for a considerable portion of the flapping arc, the outer part is limp and produces no useful force. Thus, in the turnaround, the ornithopter wastes a lot of energy and produces a limited amount of lift, relying on the inner portion of the wing. Even before the turnaround event, the wing lift is reduced because of the large dihedral angle at certain points in the flapping cycle.

As mentioned earlier, the severity of the dead-center effect is regulated by the membrane tension and spar stiffness. If the spar is relatively springy in the horizontal direction, it can keep the membrane under tension throughout the reversal. This would allow a larger portion of the wing to continue producing lift throughout the reversal. Also, the resistance to flapping around the time of reversal would be greater, lessening the dead-center effect.

However, spar springiness in the *vertical* direction is detrimental. A vertically springy spar would not keep up with the motion of the wing lever during the reversal, and so some of the crank rotation would not be imparted to the wings. In the extreme case, the spars may simply vibrate in place while the motor unwinds at a frightening speed. Most modelers try to make their spars as stiff as possible, but some have experimented with spars that are selectively springy in the horizontal but not vertical direction. This can be accomplished by using a special cross-section shape, laminated spars, or reinforcement along the top and bottom of the spar.

Despite the problems with wing reversal, the event can be exploited advantageously under some conditions. Some birds and insects clap their wings together overhead at the end of the upstroke, producing a burst of thrust as the wings clap together and then pull apart. Biplane ornithopters can also benefit from the clapping together of their wings, on either side of the body.

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Advanced Wing Designs

This chapter describes some of the more complex wing designs, which are intended to produce a more efficient flight. The conventional membrane wings are already fairly good. With current electric power systems, the flight times can run from 10 minutes to as long as 45 minutes, which is in the same league as typical RC airplanes and helicopters. There are two main ideas for improving the wing efficiency. One is to provide a more efficient airfoil cross-section. The other is to fine-tune the angles of attack experienced along the wingspan.

There are two ways of controlling the amount of wing twist. One uses aeroelastic properties, and the other uses active mechanical devices.

The most common type of wing design for ornithopters uses passive aeroelastic properties to control the twisting of the wing. In such wings, amount of twist depends on the amount of force applied. The typical membrane wing is an example of this type. Aeroelastic wings may also have a ribbed structure superficially similar to an airplane wing. The leading edge spar twists in response to lift forces acting on the wing. The twisting of the spar determines the incidence angle of the wing ribs mounted in the spar and therefore that of the wing surface itself.

Built-up wings of this sort differ from airplane wings in a number of ways: The main spar must be torsionally flexible and located at the front of the wing. There cannot be more than two spars in the wing or it will be too resistant to twisting, unless the ribs can rotate freely with respect to one of the spars. The wing covering must be able to conform to the wing and not buckle as the wing twists. This last requirement is met easily enough if a single-surface covering is used, but if the top and bottom of the wing are both to be covered, then the task becomes more difficult. One approach would be to use a flexible covering, like latex. Another method, developed by James DeLaurier and Jeremy Harris, is to split the trailing edge so that the upper and lower wing surfaces can slide past each other. They call this “shearflexing”.

For optimal gliding flight, the aeroelastic wing should have a certain amount of built-in twist. The amount of built-in twist can be adjusted so that the wing is completely flat, like an airplane wing, when the lift force is equal to the model's weight, as it is in gliding flight. This improves the gliding performance, but it may adversely affect performance during flapping flight.

As an alternative to aeroelasticity, the twisting of the wing may be controlled by mechanical devices associated with the flapping mechanism. This allows the wing twist to be set to any desired amount during the upstroke and downstroke, and it is more easily adjusted than the structural properties of the aeroelastic wing. However, this approach results in greater complexity and greater frictional power loss. It also lacks the ability to automatically increase the amount of wing twist in response to increased power input, a nice feature of aeroelastic wings.

In principle, one can improve the efficiency of an ornithopter by using a double-surface airfoil with a rounded leading edge. These airfoils have better lift over drag ratios over a wider range of attack angles than cambered, single-surface airfoils.

Aerodynamicist James DeLaurier has invoked the concept of “leading edge suction” to explain this phenomenon. Aerodynamicists typically break the force produced by an airfoil into two components: lift and drag. The drag component, by definition, is parallel and opposite to the wing’s path of motion. Lift is perpendicular to the wing path. DeLaurier breaks up the resultant force differently. He divides it into a chordwise force (parallel to the wing chord) and a normal force (perpendicular to the chord). The difference between these two systems is that DeLaurier’s frame of reference has been offset by a certain angle, equal to the angle of attack.

In the conventional system, every airfoil has a certain amount of drag. In DeLaurier’s system, the chordwise component may be either positive or negative. Typically, a thin, cambered airfoil will have a negative chordwise force (drag), whereas a more efficient airfoil with a rounded leading edge might have a positive chordwise force (thrust). What this shows is that an airfoil that (in the conventional system) has a really good lift over drag ratio when flying at high angles of attack will be able to produce thrust simply by moving up and down, without any change in incidence. According to DeLaurier, air flowing around the leading edge is what makes this possible.

A highly-efficient, airplane-like wing might seem like the ultimate ornithopter wing design. However, birds go one step farther. Their wings not only have an efficient airfoil cross-section, but also the ability to contract or lengthen as needed. Birds (and also bats) partially fold their wings on the upstroke. By decreasing the wingspan in this way, the relative flow angle is lower, allowing the wings to produce more lift with less drag than would otherwise be possible. Only a few ornithopters have had their wings articulated in quite this manner, and most attempts at wing articulation have had poor results. Yet we know from the examples in nature that this should yield very good results once it is done correctly.

If there were no birds, the ornithopters we have today would seem much closer to nature. Their lack of feathers certainly would not seem a failing, because their membranous wings are quite similar to those of insects. Yet the drive to build a more bird-like ornithopter, one having artificial feathers, is one of the remaining unachieved goals of flapping-flight research. It might not be for any practical purpose, but just for a more realistic appearance. Practical applications do rely on maneuverability, precise control, and in some cases, autonomy. Therefore, the emulation of the avian nervous system in performing these functions is a very important goal.

The use of flapping wings is one distinctive feature of animals, but equally fascinating is the ability of animals to control all parts of their bodies to optimize their efficiency and performance. When a bird makes a landing approach, it does so with full down elevator to maximize the lift produced by the tail. Meanwhile, the wings are swept forward to compensate, keeping the nose up. The bird is completely unstable at this point. Rather than using its tail for stability and control, it does just the opposite. Subtle adjustments of wing sweep and area guide the bird to a soft landing on the shortest of runways. MacCready’s QN pterosaur project showed that we are beginning to discover the secrets of animal flight control, and this is one of the most exciting areas for future work in the field of flapping-wing flight.

V. Resources

I’ve put together some resources that you may find helpful in designing and building your own ornithopters: books you might want to read, where you can buy gears, etc. Of course, I hope you will continue to participate in the Ornithopter Zone newsletter and web site as your ornithopter designs progress. You are part of an international community of ornithopter enthusiasts, and it is through the sharing of ideas that we have achieved so much in the last few decades. The *Flapping Wings* newsletter is also an ideal way to establish a permanent record of your accomplishments.

For *Flapping Wings* subscription information, write to The Ornithopter Zone, 582 Laurelton Road, Rochester NY 14609 USA, or visit our web site: www.ornithopter.org.

Suggested Reading

Electric Motor Handbook, by Robert J. Boucher
This book fully explains, in technical terms, everything you need to know about the use of electric motors in RC models.

The Miracle of Flight, by Stephen Dalton
This non-technical book covers all aspects of natural flight, as well as man-made aircraft. The sequential photos of birds and insects in flight are fascinating.

Indoor Flying Models, by Lew Gitlow
If you are interested in indoor flying model competitions, this book is crammed full of information that will be useful to you. Some information is specific to ornithopters.

How Birds Fly, by David Goodnow
You already know how birds fly, but this book reveals some of the special techniques birds use for takeoffs and landings, etc. It also includes many sequential photos. Good for children.

Basics of RC Model Aircraft Design, by Andy Lennon
A comprehensive guide to designing radio control model airplanes.

Birdflight as the Basis of Aviation, by Otto Lilienthal
Originally published in 1889, this book was intended to aid experimenters in the application of bird flight principles to the design of aircraft. What could be more perfect?

Flying Models, by Don Ross
Don Ross describes rubber, CO_2, electric powered, and small RC airplanes. This book is a good introduction to the equipment and building techniques used by hobbyists.

Avian Flight, by John J. Videler
This book comprehensively describes the recent scientific research into bird flight.

Building and Flying Indoor Model Airplanes, by Ron Williams
Great information on how to build indoor flying models and use them in competition.

Suppliers

Please support your local hobby shop and hardware store. They will have many of the items you need for building ornithopters. Some specialized items will need to be ordered from the following sources.

The Ornithopter Zone 582 Laurelton Road Rochester NY 14609 www.ornithopter.org (585) 482-3481	Ornithopter kits and publications.
McMaster-Carr Supply Co. 600 N County Line Rd. Elmhurst, IL 60126 www.mcmaster.com (630) 833-0300	Plastic and metal stock, industrial laminates, fasteners.
Stock Drive Products 2101 Turnpike, Box 5416 New Hyde Park, New York 11042 www.sdp-si.com (516) 328-3300	Gears, shafts, bearings, and other mechanical components.
Boca Bearing Company 755 NW 17th Ave. #107 Delray Beach, FL 33445 www.bocabearings.com (800) 332-3256	Bearings.
Stevens International 706 N. White Horse Pike Magnolia NJ 08049 www.stevenshobby.com (856) 435-1555	Plastic cluster gears for small electric ornithopters.
Hang-Em High Fabrics 1420 Yale Ave. Richmond VA 23224 ecom.citystar.com/hang-em-high (804) 233-6155	Fabric, carbon rods.

CST – The Composite Store PO Box 622 Tehachapi CA 93581 www.cstsales.com (800) 338-1278	A wide range of composite materials.
Didel CH-1092 Belmont/Lausanne Switzerland www.didel.com Tel. +41 21 728-6156	Micro-size motors and gears.
Plantraco Ltd. 1105 8th Street East Saskatoon, SK S7H 0S3 Canada www.plantraco.com (306) 955-1836	Micro RC equipment.
Sky Hooks & Rigging 2206 Towne Blvd. Oakville, ON L6H 5H4 Canada www.skyhooks.ca (905) 257-2101	Various items for small RC flying.
A2Z Corp 1530 W Tufts Ave. Unit B Englewood CO 80110 www.peck-polymers.com/store (720) 833-9300	Supplies for indoor and rubber-powered models.

Drill Bit Sizes with Decimal Inch Equivalents

From Scrollsaw Association of the World (saw-online.com). Used with permission.

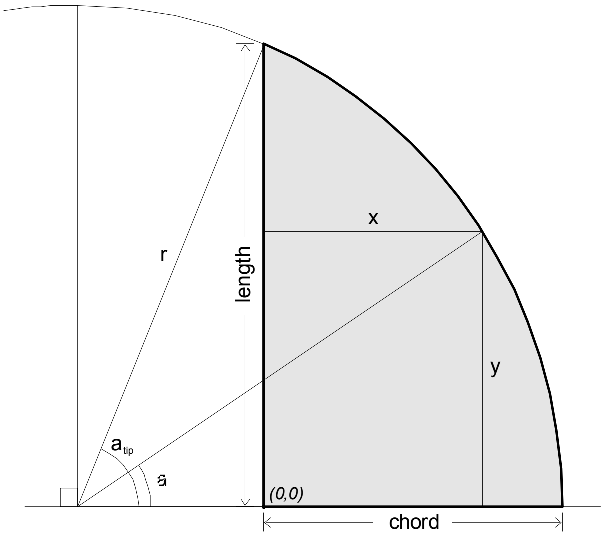
Drill Bit Hole Diameters							
Metric Size		Fractional Size		Wire Size		Letter Size	
.1 mm	.0039	1/64	.0156	80	.0135	A	.2340
.2 mm	.0079	1/32	.0312	79	.0145	B	.2380
.3 mm	.0118	3/64	.0469	78	.0160	C	.2420
.4 mm	.0157	1/16	.0625	77	.0180	D	.2460
.5 mm	.0197	5/64	.0781	76	.0200	E	.2500
.6 mm	.0238	3/32	.0938	75	.0210	F	.2570
.7 mm	.0276	7/64	.1094	74	.0225	G	.2610
.8 mm	.0315	1/8	.1250	73	.0240	H	.2660
.9 mm	.0354	9/64	.1408	72	.0250	I	.2720
1 mm	.0394	5/32	.1562	71	.0260	J	.2770
2 mm	.0787	11/64	.1719	70	.0280	K	.2810
3 mm	.1181	3/16	.1875	69	.0292	L	.2900
4 mm	.1575	13/64	.2031	68	.0310	M	.2950
5 mm	.1968	7/32	.2188	67	.0320	N	.3020
6 mm	.2362	15/64	.2344	66	.0330	O	.3180
7 mm	.2756	1/4	.2500	65	.0350	P	.3230
8 mm	.3150	17/64	.2656	64	.0360	Q	.3320
9 mm	.3543	9/32	.2812	63	.0370	R	.3390
10 mm	.3937	19/64	.2980	62	.0380	S	.3480
11 mm	.4331	5/16	.3125	61	.0390	T	.3580
12 mm	.4724	21/64	.3261	60	.0400	U	.3680
13 mm	.5118	11/32	.3438	59	.0410	V	.3770
14 mm	.5512	23/64	.3594	58	.0420	W	.3860
15 mm	.5906	3/8	.3750	57	.0430	X	.3970
16 mm	.6299	25/64	.3906	56	.0465	Y	.4040
17 mm	.6693	13/32	.4062	55	.0520	Z	.4130
18 mm	.7087	27/64	.4212	54	.0550		
19 mm	.7480	7/16	.4375	53	.0595		
20 mm	.7874	29/64	.4531	52	.0635		
21 mm	.8268	15/32	.4688	51	.0670		
22 mm	.8661	31/64	.4844	50	.0700		
23 mm	.9055	1/2	.5000	49	.0730		
24 mm	.9449	33/64	.5156	48	.0760		
25 mm	.9843	17/32	.5312	47	.0785		
		35/64	.5469	46	.0810		
		9/16	.5625	45	.0820		
		37/64	.5781	44	.0860		
		19/32	.5938	43	.0890		
		39/64	.6094	42	.0935		
		5/8	.6250	41	.0960		
		41/64	.6406	40	.0980		
		21/32	.6562	39	.0995		
		43.64	.6719	38	.1015		
		11/16	.6875	37	.1040		
		45/64	.7031	36	.1065		
		23/32	.7188	35	.1100		
		47/64	.7332	34	.1110		
		3/4	.7500	33	.1130		
		49/64	.7656	32	.1160		
		25/32	.7800	31	.1200		
		51/64	.7969	30	.1285		
		13/16	.8125	29	.1360		
		53/64	.8281	28	.1405		
		27/32	.8438	27	.1440		
		55/64	.8580	26	.1470		
		7/8	.8750	25	.1495		
		57/64	.8892	24	.1520		
		29/32	.9062	23	.1540		
		59/64	.9219	22	.1570		
		15/16	.9375	21	.1590		
		61/64	.9531	20	.1610		
		63/64	.9844	19	.1660		
		1	1.000	18	.1695		
				17	.1730		
				16	.1770		
				15	.1800		
				14	.1820		
				13	.1850		
				12	.1890		
				11	.1910		
				10	.1935		
				9	.1960		
				8	.1990		
				7	.2010		
				6	.2040		
				5	.2055		
				4	.2090		
				3	.2130		
				2	.2210		
				1	.2280		

Tap Drills

From LittleMachineShop.com. Used with permission.

Screw Size	Threads Per Inch	Tap Drill				Clearance Drill			
		75% Thread for Aluminum, Brass, & Plastics		50% Thread for Steel, Stainless, & Iron		Close Fit		Free Fit	
		Drill Size	Decimal Equiv.	Drill Size	Decimal Equiv.	Drill Size	Decimal Equiv.	Drill Size	Decimal Equiv.
0	80	3/64	.0469	55	.0520	52	.0635	50	.0700
1	64	53	.0595	1/16	.0625	48	.0760	46	.0810
	72	53	.0595	52	.0635				
2	56	50	.0700	49	.0730	43	.0890	41	.0960
	64	50	.0700	48	.0760				
3	48	47	.0785	44	.0860	37	.1040	35	.1100
	56	45	.0820	43	.0890				
4	40	43	.0890	41	.0960	32	.1160	30	.1285
	48	42	.0935	40	.0980				
5	40	38	.1015	7/64	.1094	30	.1285	29	.1360
	44	37	.1040	35	.1100				
6	32	36	.1065	32	.1160	27	.1440	25	.1495
	40	33	.1130	31	.1200				
8	32	29	.1360	27	.1440	18	.1695	16	.1770
	36	29	.1360	26	.1470				
10	24	25	.1495	20	.1610	9	.1960	7	.2010
	32	21	.1590	18	.1695				
12	24	16	.1770	12	.1890	2	.2210	1	.2280
	28	14	.1820	10	.1935				
	32	13	.1850	9	.1960				
1/4	20	7	.2010	7/32	.2188	F	.2570	H	.2660
	28	3	.2130	1	.2280				
	32	7/32	.2188	1	.2280				
5/16	18	F	.2570	J	.2770	P	.3230	Q	.3320
	24	I	.2720	9/32	.2812				
	32	9/32	.2812	L	.2900				
3/8	16	5/16	.3125	Q	.3320	W	.3860	X	.3970
	24	Q	.3320	S	.3480				
	32	11/32	.3438	T	.3580				
7/16	14	U	.3680	25/64	.3906	29/64	.4531	15/32	.4687
	20	25/64	.3906	13/32	.4062				
	28	Y	.4040	Z	.4130				
1/2	13	27/64	.4219	29/64	.4531	33/64	.5156	17/32	.5312
	20	29/64	.4531	15/32	.4688				
	28	15/32	.4688	15/32	.4688				

Drawing Wing Outlines



Drawing an Arc:

Given the length and root chord of the wing, first calculate the required degrees of arc and the radius of the curve:

$a_{tip} = 180 – 2 \tan^{-1}$ (length/chord)

r = length / sin(a_{tip})

Then, plot a series of points using the formulae below and selected values of angle *a* ranging from zero to a_{tip}.

y = r sin(a)

x = chord + r (cos(a)-1)

For Elliptical Wing:

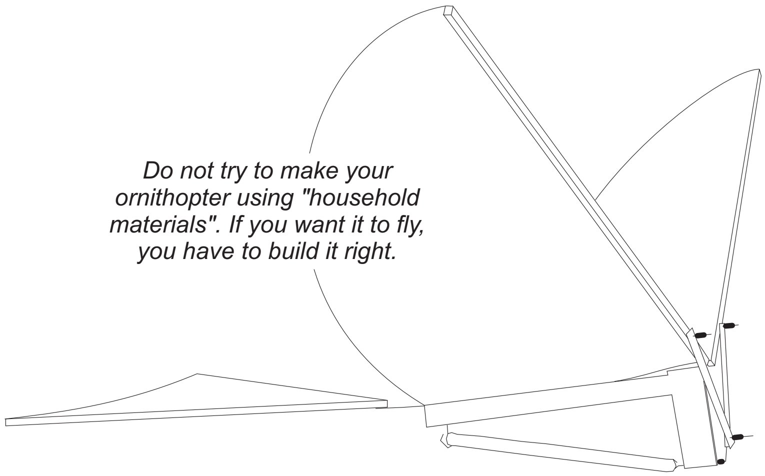
Plot a series of points using the formulae below, and *a* values ranging from 0 to 90 degrees:

y = length * sin(a)

x = chord * cos(a)

Notes:

Do not try to make your ornithopter using "household materials". If you want it to fly, you have to build it right.



FREEBIRD

THE ORIGINAL D.I.Y. ORNITHOPTER!

Wingspan: 16 inches
Weight: 1/4 ounce

The Ornithopter Zone
www.ornithopter.org

Required Materials

Balsa wood:
- 1/8" square stick
- 3/32" square stick
- 1/8 x 5/16" stick
- 1/8 x 1/2" stick

Model aircraft plywood, 1/32" thick
Steel music wire, 1/32" diameter
Aluminum (or brass) tubing, 1/16" diameter
~~Small plastic bead with 1/32" hole~~
Insulation stripped from 22 gauge wire
Model airplane rubber , 1/8" wide by 18" long
Model airplane tissue (6" x 20" sheet)

Instead of the plastic bead, use a 1/8" long section of the metal tubing.

Tools and Glue

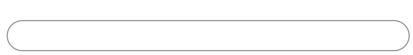
White glue
Epoxy or CA glue
Hobby knife (or single edge razor blade)
Needle-nose cutting pliers
Straight pin
Sandpaper
Ruler
Solid cardboard to cut on
Wax paper

1 **Gather Materials.** Your local hobby shop or **sigmfg.com** should have most of the items listed above. Do not make substitutions, especially with the rubber band. Office-grade replacements will result in an ornithopter that barely flies.

Prepare the Wood Parts. Using the hobby knife, with cardboard to protect your work surface, cut balsa to the following sizes:

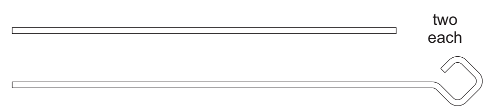
1/8" square stick - two 8" lengths (wing spars)
3/32" square stick - two 7" lengths (tail pieces)
1/8 x 5/16" stick - one 5" piece (motor stick)
1/8 x 1/2" stick - one 1-1/8" piece (strut)

Also cut two strips of aircraft plywood, 3/16 by 2-1/8". You can round the ends with sandpaper. These are the connecting rods.



make two from plywood

2 **Wire Parts.** With pliers, cut two 2" lengths of music wire and two 2-3/4" lengths. With the two longer pieces, use the pliers to form a small hook in one end, about 1/4" wide.

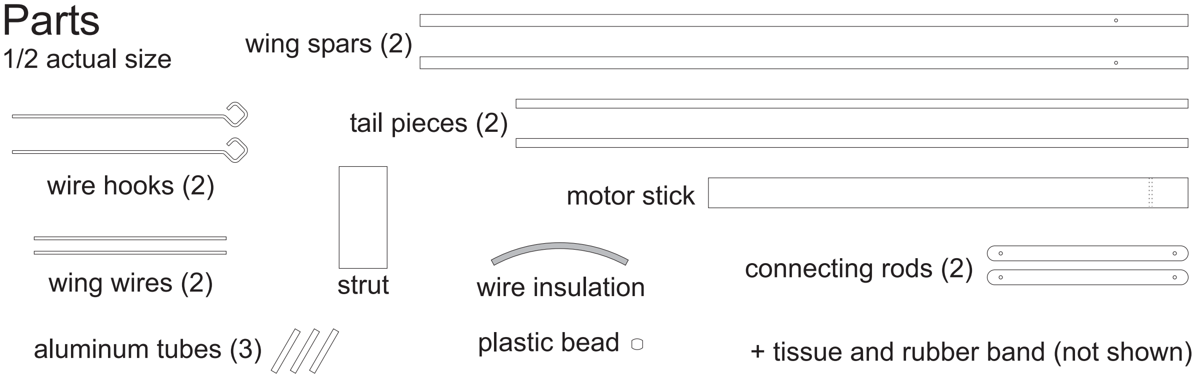


Aluminum Tubing. Press down with the hobby knife to cut aluminum tubing. Cut three 1/2" lengths. Sand the ends until they are smooth and perpendicular.

side view, enlarged

Also cut a 1/8" length of tubing to substitute for the plastic bead shown later in the instructions. Smooth off the end of the tube before cutting.

Parts
1/2 actual size

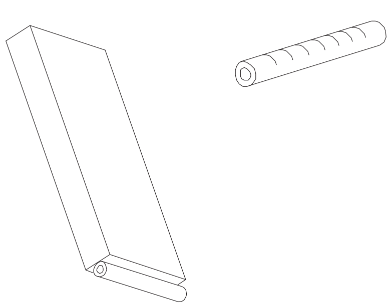


3 **Drilling Holes.** You can use the sharp end of the wire you cut to drill holes. Work on a flat surface protected with cardboard. The wire is sharp, so don't support the wood with your finger. Keep the wire straight up and down, and twist it between your fingers to make a hole.

Holes should be made 3/4" from one end of each wing spar and 3/8" from one end of the motor stick, as shown above.
The plywood is much harder than balsa, so make make a starter hole first, using a straight pin. Make holes exactly 1-3/4" apart in the connecting rods.

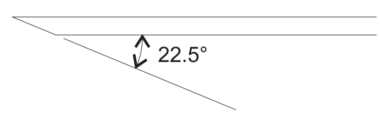
At this stage, all parts should look like the drawing at the top of the page.

4 **Crank Bearing.** Glue the metal tube to one end of the balsa wood strut using epoxy or CA glue. Optionally, you can file some grooves first to improve the bond strength. This doesn't seem to be necessary, though.

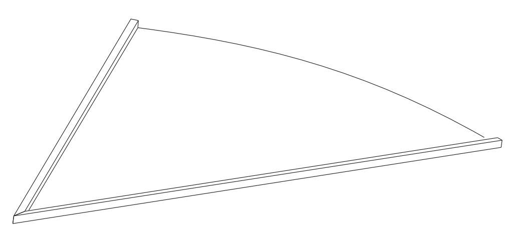


5 **Wing and Tail Tissue.** On the next page, you will find outlines for the wings and tail. Trace the outlines onto the tissue paper, arranging them as shown here. Flip the tissue over so you can trace both wing halves. Cut out the wings, both in one piece, and cut out the tail. Save the leftover tissue.

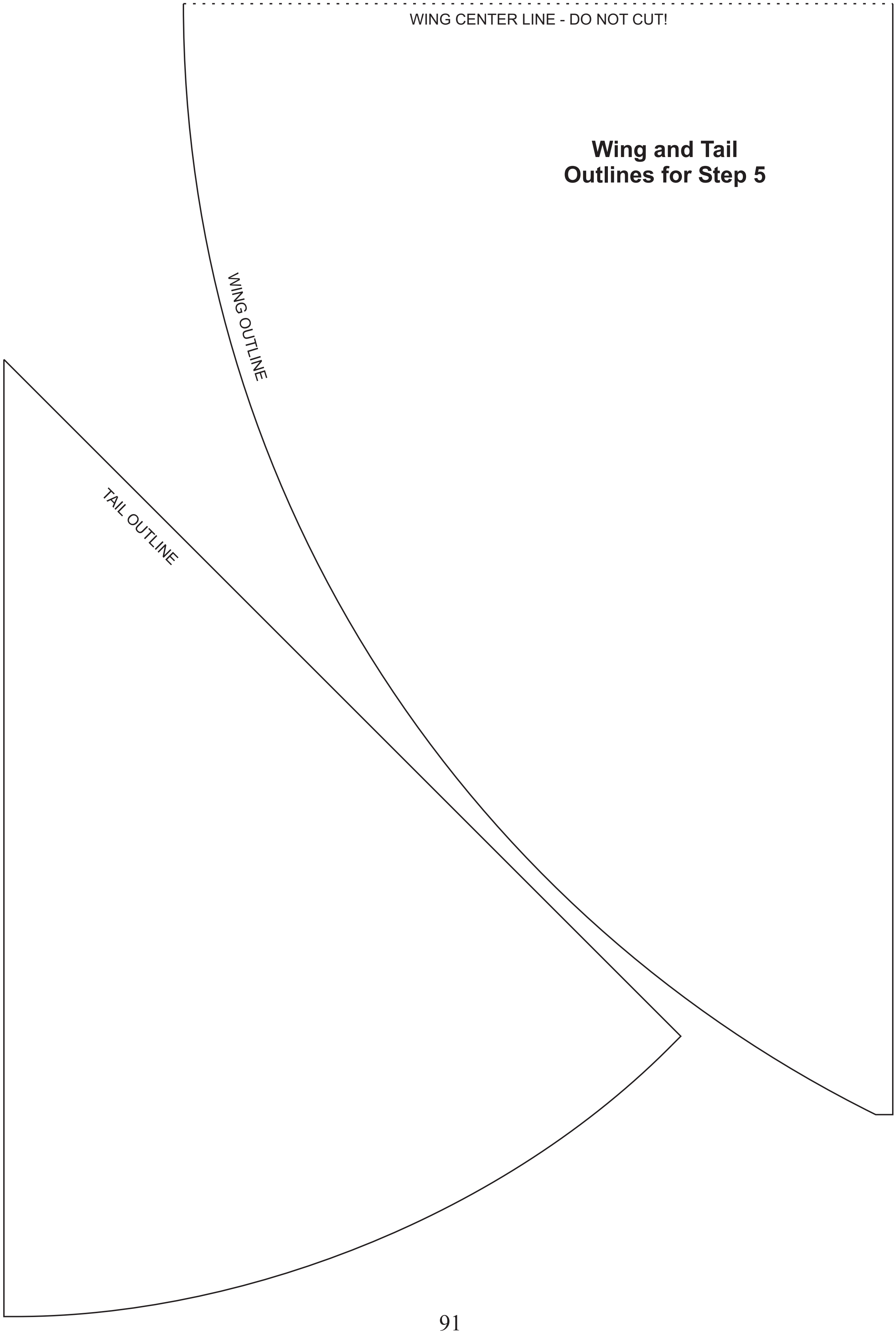
6 **Tail Pieces.** Cut a 22.5° angle at the end of each tail piece. Use the drawing to make this cut accurately.



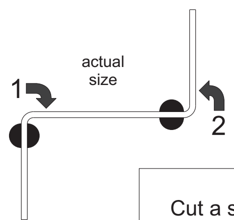
7 **Tail Assembly.** On wax paper, apply glue to the bevel end of each tail piece. Spread a thin layer of glue along the length of each tail piece and glue them onto the tail tissue, joined at the bevel.



Wing and Tail Outlines for Step 5

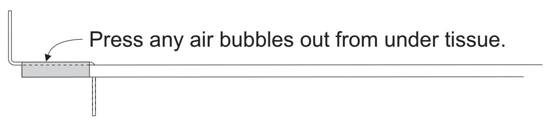


8 **Wing Spars.** Using pliers, bend the wing wires precisely as shown below. Grip with pliers where indicated ( ). Try for sharp 90° bends, and make sure the part will lay flat after bending.

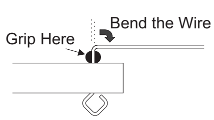


Apply glue and insert the wire into the hole in the wing spar. Glue the wire to the spar.

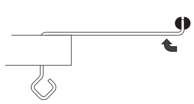
Cut a strip of tissue about this size. Apply a thin layer of glue. Wrap the tissue around the wire and spar.



9 **Wire Hook.** Apply glue, then insert a wire hook through the hole in the motor stick. The hook opening should be on the right.

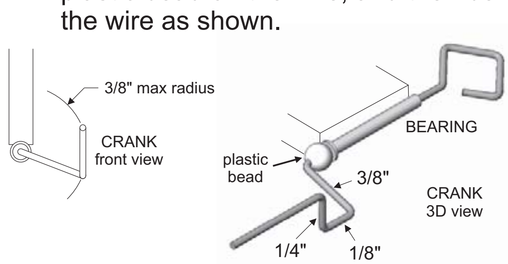


Bend wire as shown. While bending, do not touch the wood or it will break.

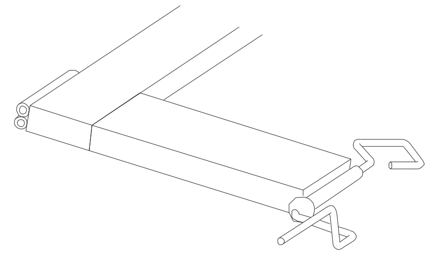


Bend once more at wire end, *straight up and down*. Glue the wire onto the motor stick.

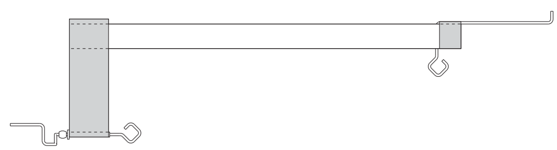
10 **Crank Wire.** Slide the other hook wire through the crank bearing tube. Put the plastic bead on the wire, and then bend the wire as shown.



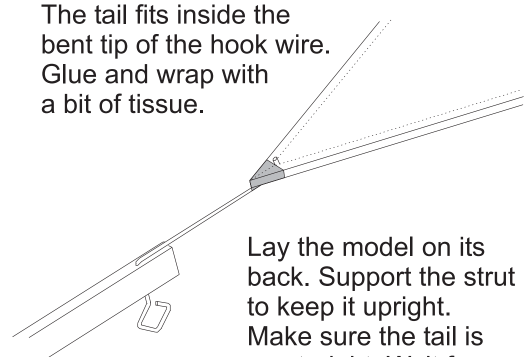
11 **Body Assembly.** Glue together the wing hinge tubes, strut, and motor stick as shown. Lay flat on wax paper until dry.



12 **Body Assembly, Continued.** Reinforce the body glue joints as you did with the wing spars. Use four layers of tissue cut to size.



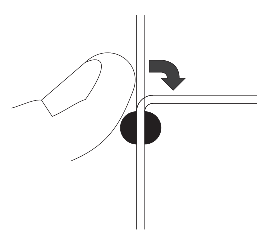
13 **Tail Placement.** The tail fits inside the bent tip of the hook wire. Glue and wrap with a bit of tissue.



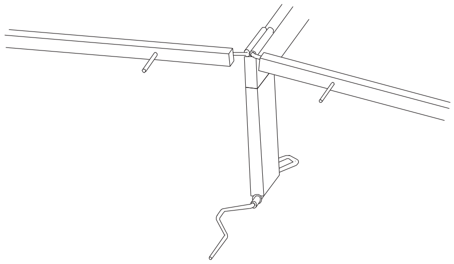
Lay the model on its back. Support the strut to keep it upright. Make sure the tail is on straight. Wait for the glue to dry.

To bend wire: Position the pliers 1/32" from where you want the bend. Squeeze the pliers tightly while bending.

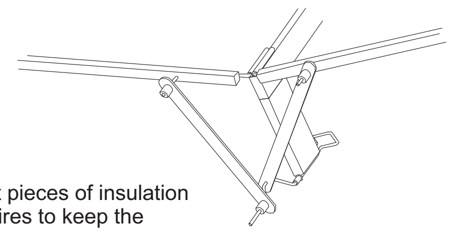
Pliers with grooves across them work much better for holding the wire.



14 **Wing Installation.** Scrape any excess glue from the wing wires. When the tail is dry, pick up the model and gently insert the wing wires into the wing hinge tubes.



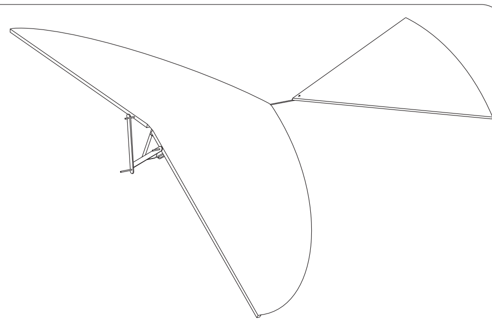
15 **Flapping Mechanism.** Slide a connecting rod onto the crank wire. Wiggle it past the first two bends in the wire. Fit the other end onto the wing wire for the bird's left wing. Then install the other connecting rod on the outer part of the crank and the right wing.



Twist short pieces of insulation onto the wires to keep the connecting rods in place. Watch out for sharp wire ends, and support the wires from behind so they don't bend.

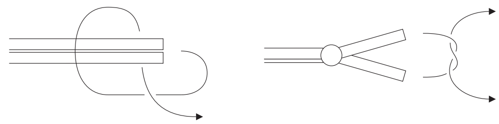
Wings must be 90 degrees from body!

16



Wing Tissue. Throughout this step, hold the wings in the "down" position, and be sure the wing wires stay all the way back in their tubes. Spread a thin layer of glue on the top of each wing spar and attach the straight leading edge of the wing tissue there. Allow the tissue to center itself naturally as you glue it to the top of the motor stick.

17 **Rubber Band.** Hold together the ends of the rubber. Tie a knot as shown, forming a large rubber band. Then tie the free ends together to secure. Do not install the rubber band on the model until all glue is completely dry. Then, *double the rubber band* and hook it onto the motor hooks, with the knot in the back.



18 **Before You Fly!** Your Freebird will not fly until you make these adjustments.

First, ***bend the tail wire up slightly***, about five degrees. Do not touch or use any wooden parts for leverage when you do this or they will break.

For test flights, turn the crank about 50 times to wind up the rubber band. After adjustments, you can wind up to 120 turns dry, or 220 with lubrication. Dry operation shortens the life of the rubber band. Vegetable oil will work.

Launch with a smooth horizontal motion, with the body inclined 20° from horizontal. Do not *throw*.

Sharp turn followed by crash: Add weight to the wingtip on the *outside* of the turn. You can use a straight pin for this. Adjust weight as needed. Winding the opposite direction may also solve this problem.

Nose dive: Bend the tail up slightly.

Stall (slowing almost to a stop and then losing height)**:** Reduce the tail angle slightly.

Errors in the strut length or the hole spacing of the connecting rods can cause a nose dive or stall.

With proper adjustments, the Freebird will fly in a large circle for up to 30 seconds (dry motor) or up to one minute with lubrication.