FALL 2001

Flapping Wings

THE ORNITHOPTER SOCIETY NEWSLETTER

A SPREADSHEET FOR STUDYING AND DESIGNING ORNITHOPTER WINGS

By Francis D. Reynolds

The author worked on RC ornithopter design for some years in the early 1990s. Some of that work was described and photos shown in this newsletter several years ago. The flapper design I finally settled on, designed, and partially built (but never completed and flew) has 10-foot-span, airfoil-type wings, and is glow-engine powered. It has a number of advanced features, but got too complex and too heavy.

I am indebted to a number of members of this Ornithopter Society and to two partners, Rob Jenny and Will Kuhnle, for many of the ideas used, and to my son Greg Reynolds for suggesting the use of computer-spreadsheet analysis during the wing design. That spreadsheet work is the subject of this article. I think some of you will find the following design methods useful.

Like most model airplane "designing," model ornithopter design is often no more than drawing "plans" based on other successful ornithopters; or upon some original ideas, but with little engineering. Unfortunately this simple "estimate, build, and try it" approach results in many more ornithopter failures than it does model airplane failures, because ornithopter mechanics and flapping-wing aerodynamics are much more complex and less understood than those of fixed-wing aircraft.

The following more-technical approach to ornithopter design requires a little understanding of basic aerodynamics and trigonometry, but many of the readers of this newsletter will have more than adequate prerequisites. Some of you are probably already using these or similar analytical methods. Horst Raebiger in Germany sent me some of his ornithopter-wing spreadsheet work, and much of it is quite similar to mine.

We know that in a fixed-wing airplane the sole purpose of the wing is to develop lift; we use propellers to provide the thrust. But birds eliminate the need for propellers by flapping specially designed wings that produce both lift *and thrust.* Easier said than done. It is obvious to us flapper types why humans were able to develop propeller-driven flying machines first. Leonardo da Vinci's sketches were only simple dreams, with little technology to back them up. There are still no successful man-carrying ornithopters, but we are bound to see them soon.

Like an airplane, a bird's forward motion develops the lift (except in hovering modes). The vertical component of motion of the flapping wings develops the thrust, just as the rotation of a propeller does. Most of the thrust of a propeller is developed near the tips where the velocity component due to rotation is the greatest. Likewise, flapping wings develop most of their thrust near the tips where their vertical-velocity component is the greatest. Thrust, like lift, varies as the square of the velocity (vertical flapping velocity in this case).

A flapping wing is like a propeller blade that turns a partial revolution and then reverses direction. It has to reverse because animals aren't equipped with joints that permit continuous rotation. Bird and ornithopter wings must twist as well as flap, to optimize the thrust by maintaining the proper effective angle of attack in all parts of the wing at all times. Prop blades are twisted for the same reason. Flapping wings must also reverse the direction of the twist between the downstrokes and the upstrokes. Most ornithopters are designed to provide the needed wing twists automatically by the way the wing membrane is supported and/or by torsion flexure of the wing spars. A racing ornithopter or bird must use more wing twist to keep the net thrust positive at higher speeds, just as a racing airplane uses a higher prop pitch.

Different birds and insects use several different flapping-wing flight modes, but the following is limited to the basic forward-flight mode. Throughout the downstrokes the wings can provide positive lift and positive thrust. The thrust drops to zero momentarily when the wing's vertical motion stops at the top and bottom of the strokes. On the *upstrokes*, which contribute less than the downstrokes, we can still achieve net positive lift, but we must suffer some negative lift at the tips if any thrust is to be generated there. And upstroke *thrust* must be slightly negative over the inboard portions of the wing if these areas are generating lift. On the upstrokes no part of the wing can provide both positive lift and positive thrust at the same time. This can all be seen in the accompanying curves.

The analytical methods to be described were used to design an admittedly complex and sophisticated ornithopter (too complex for its own good). But these methods will also be useful in designing simple membrane-wing ornithopters.

To optimize the design of flapping wings we need to know just what will be going on in each part of those wings in flight, not only from wing root to wing tip, but during each part of the flapping cycle. The spreadsheet method lets us look at all of that on one sheet of paper (or the computer screen) for each different set of design assumptions. Computer spreadsheet programs can keep many factors all neatly sorted out. They even do complex math for us instantly, and automatically redo the math and update the answers every time we make a change in any variable.

The spreadsheets program is found in my MS Windows 95 computer by these steps: Start, Programs, Finance and Productivity, MS Works 4, MS Works 4 (again), Works Tools tab, Works Task Launcher, and finally, Spreadsheet. (Why they had to hide it so well I don't know.)

And if you haven't used spreadsheets before you may need to borrow a book, take a class, or get a friend's help in learning how. We can't simply tell the computer, "Make me a spreadsheet for the design of my ornithopter wing." We have to tell the spreadsheet program how we want the wing designed by writing a simple program for our proposed design. Don't let "write a program" scare you. I have never done any computer programming in the usual sense, but telling the spreadsheet program what I wanted to see in terms of an ornithopter wing wasn't too difficult. Basically one needs to decide which of the design variables need to be listed in columns, and then tell the program what mathematical relationship each column bears to the column on its left, or to several earlier columns in combination.

This sample spreadsheet, one in a series of about forty sheets in that phase of my ornithopter wing-design study, was developed for my own use and refers to my own ornithopter design, so the specific numbers in it are of little interest here.

This spreadsheet example presents a number of factors for each tenth of the semi-span out from the body, first for the middle of the downstroke, and then for the middle of the upstroke. The factors included are, from left to right: The wing station for which a line applies, in tenths of the semi-span. The vertical velocity component of that station due to flapping under the assumed values of span, flapping rate, and flapping angle assumed above. The angle in degrees at which that wing station will be feathered (operating at zero angle of attack). The resultant velocity (feet per second) of that wing station at that instant in time due to the combination of the forward velocity of the ornithopter and the vertical flapping velocity of that station. The wing twist angle in degrees needed at that station (the algebraic sum of the feathered angle and the angle of attack, alpha, desired at that station and shown in the next column). The lift coefficient that will be produced at that station under these conditions, taken from lift and drag vs. angle-of-attack curves of the airfoil specified, at the operating Reynolds Number of this ornithopter under these assumptions. The resultant force in pounds (or kilograms) generated at that wing station due to its resultant velocity and angle of attack at that moment in time. The vertical or lift component of that resultant force. And last, the thrust or horizontal component of the force at that wing station at that moment.

Then we have the spreadsheet program algebraically add all of the lift values, and separately add the thrust values of all ten stations, to give us the total lift and total thrust for the entire wing at mid downstroke and for mid upstroke for those assumed conditions. A different spreadsheet analysis is required to integrate the entire flapping cycle into average lift and average thrust under these conditions. Is the available lift equal to or greater than the predicted total weight? Then we can estimate the drag of our bird and decide what rate of climb we need, and check to see if the thrust shown on that sheet will be enough.

It is easier to "see" what the spreadsheets are telling us if we can look at the results in the form of curves. Included here is one useful form of curves that can be plotted from this type of spreadsheet data.

In this iteration I assumed uniform twisting of the wing from the root out to 80% of the semi-span, and from there made the tip section rigid, so the pitch (total twist) angle of the wing remains constant from there to the tip. The helically twisted inboard portion was designed to operate at the angle-of-attack for maximum Lift / Drag for efficiency. But since there is no further twisting beyond eight tenths of the semi-span, the effective angles of attack rise higher out there, producing higher coefficients and more thrust in both the downstrokes and the upstrokes.

Not happy with the answers you see on your first spreadsheet? Change the speed, and/or the span, the chord, the flapping rate, the flapping angle, the angles of attack, the airfoil, the weight, the drag, or something else, and run another spreadsheet. And keep changing it until you have what looks like the best compromise. Design is an iterative process. With lots of savvy and lots of experience we may be able to come close to an optimum design on the first try, but it isn't likely. Changing one variable at a time and running more spreadsheets is many times easier, faster, less expensive, and much more precise than trying to flight test all of these changes in actual models.

On the other hand, flight-testing is fun (as well as frustrating), and it can teach us practical lessons that we will never learn by working with engineering data alone. We need both, just like Boeing does.

I am sure I speak for all of the readers of this newsletter when I congratulate Sean Frawley, and his predecessors, Nathan Chronister and others, on their hard work in providing us with this excellent ornithopter-fraternity newsletter and the ornithopter website. A big Thank You, Gentlemen.

Write or email the editor to get your copy of the spreadsheets and graphs

From the editor

I would like everyone to be aware that I will be sending out the next few issues in very rapid succession . So please rush your renewal payments if you don't want to miss any action! Also, if there is a large enough demand, I can set up an online renewal service using credit cards. Please inform me if you are interested.

From the Archives: Winter '95

Electric Ornithopter Discovery

Despite my best efforts, there are still a lot of people, throughout the world, building ornithopters without knowing of others who are working on the problem as well. Sometimes I learn about such people, and sometimes I am amazed to see that they have gotten even farther than the rest of us. One such person is Horst Rabiger of Germany. His 3m span, 4.5 kg electric ornithopters, first flown in 1989, is among the most advanced of modern experimental ornithopters. While his machine cannot take off from the ground, as could P.H. Spencer's radio-controlled ornithopter, it is able to alternate between flapping and gliding flight and may be the first ornithopter to do so. The wing design is highly efficient, using an elastic wing covering to allow wrinkle-free twisting of a thick (Clark Y, 11.7%) airfoil. This technique is an alternative to the shear-flexing used by Harris and DeLaurier. The elastic covering is very thin, so a large number of ribs is required. Each wing is supported by two internal spars, and the structure is designed for torsional flexibility. The following letter from Rabiger (31 March 1994) tells more about his ornithopter.

-Nathan Chronister

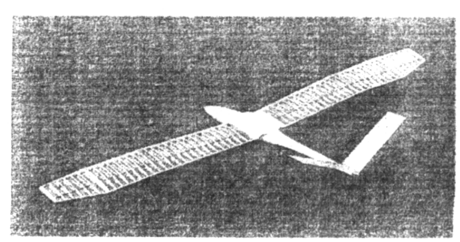
Unfortunately my English is not the best. My daughter must assist me in writing these letters. Therefore I am able to give you merely a rough description. The models are radio controlled. I can choose among gliding and powered flight as often as I like. A cycle of the flapping wing takes about 0.6 seconds. As the wings flap no vertical movement of the body is to be seen.

I have started working on the ornithopter problem some 25 years ago. 1989 I have achieved a maximal flight duration (with flapping wings) of about one minute (flying a circle), followed by one or two minutes gliding flight. The flights usually come to an end after 10 to 20 seconds. The ornithopters always descend steeply because of the aero modeller intending the model to reach altitude flying too slow (stalling speed).

I am using 14 nickel-cadmium cells in series, RED Amp, Panasonic, capacity 1.2 Ah. They provide sufficient energy for a flight lasting about 5 minutes. More than 150 to 200W are not permissible because of the slight torsion of the airfoil and the profile data.

The total transmission ratio of the model EV7 (1992) I am using is about 120 to 160:1 and the transmission consists of gearwheels only. Sometimes I am using planetary gears. The angle of incidence of the airfoil to the body is constant. The theoretical wing twist is shown on the picture "Abb. 48" of the enclosed data. I am using an elastic foil. It is fixed with a small adhesive splicing. The wing twist is exclusively caused by aerodynamic forces "working" against a spring and not by the energy. I am afraid I cannot give you any further information about my flexible wing design since I have not applied for a patent so far.

Below: Rabiger's electric ornithopter has a very sailplane-like appearance and must be very efficient



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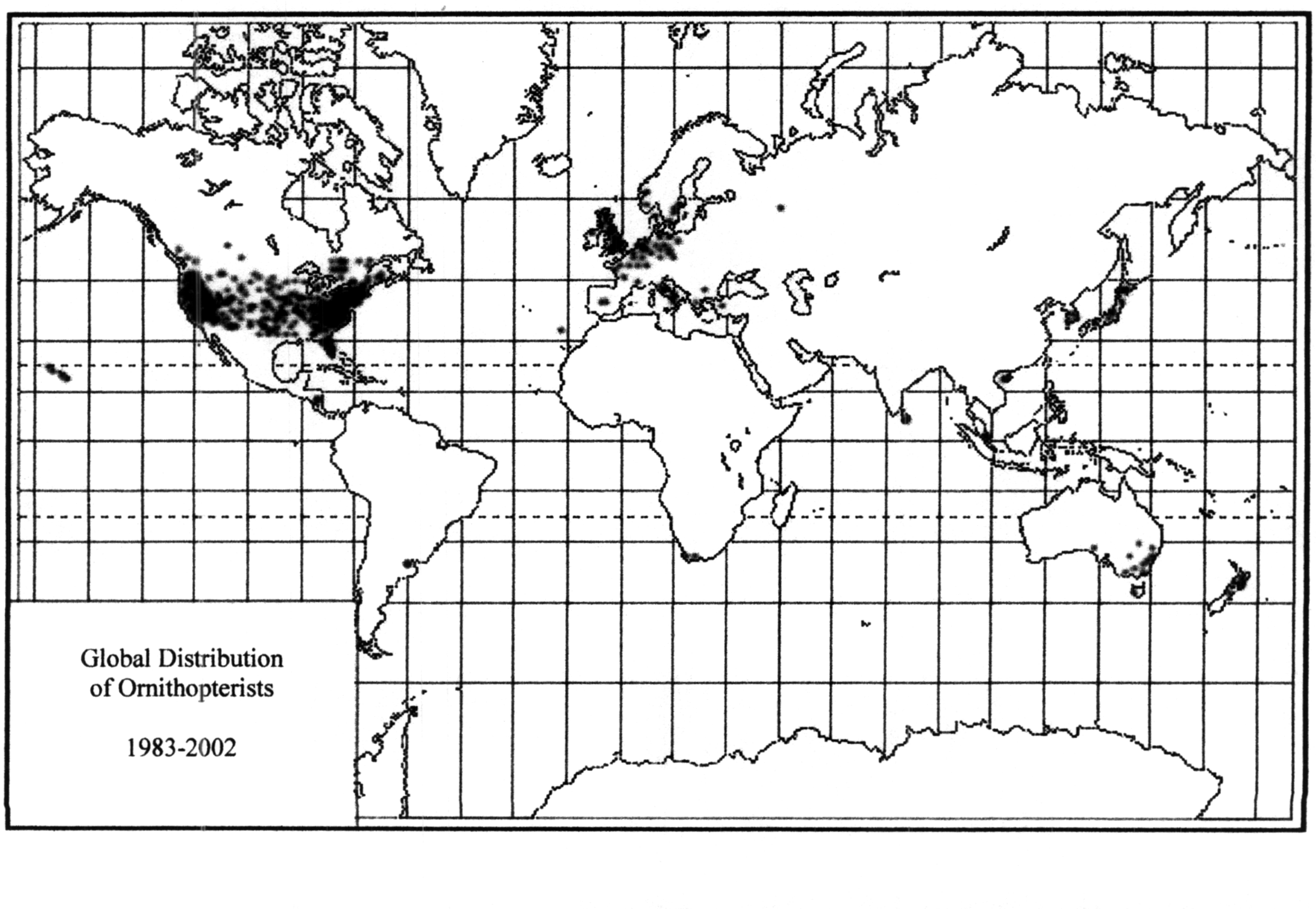
Join the Ornithopter Society or renew your membership: Dues are $12 per year in the USA. Dues outside the USA are $17 US per year. Checks are payable to *Sean Frawley*.

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

www.ornithopter.org



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