Lift during wing upstroke

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Version 8.0

Content

1. Introduction

The basic principle of lift and thrust generation in flapping flight has already been described by Erich von Holst[1], 1943. In his functional scheme (see following Figure 1) the location of the centre of the lift is represented by a wing section which is shiftable along the half span of the wing. On the top of the stroke it is shifted towards the wing tip and at the bottom point to the wing root. In this way, seen over a whole flapping period, while maintaining the lift force F_L the thrust F_T on downstroke can get larger than the backward directed additional drag $-F_T$ on upstroke.

This means that also on upstroke the lift can be about of the same size as in gliding. At the same time the upstroke plays an important role in the generation of thrust of whole flapping period, even if it self does not generate positive thrust. For an optimal design of the wing upstroke is necessary a concentration of the lift in the mid-span. The related, technical relationships how it can happen at least approximately are to be described here.

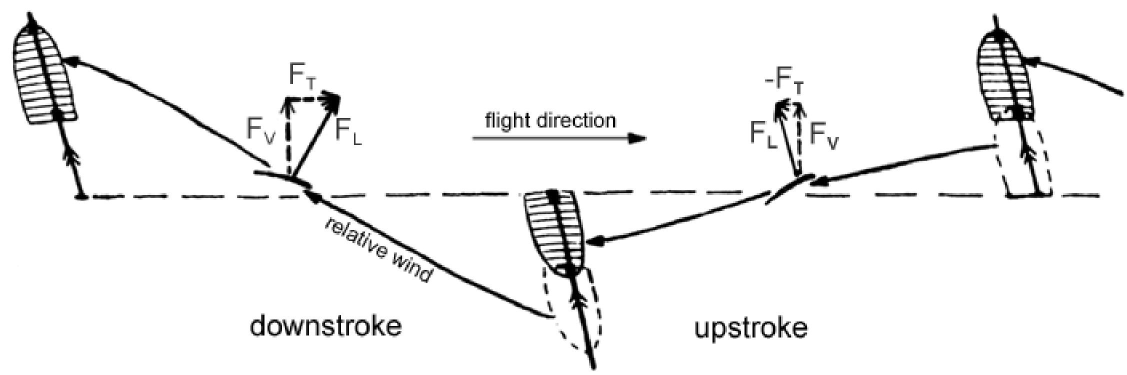

Figure 1. Basic principle of lift and thrust generation by lift displacement in the flight of birds, by Erich von Holst[1], 1943

In the research of the bird flight has always been discussed whether the wing upstroke happened, with muscle strength or aerodynamic forces. To clarify the corresponding physical processes, first with a technical flapping wing a theoretically experiment is executed here. For this, a wing on its wing root is rotatable mounted in a wind tunnel (see following Figure 2). With airflow from the front and positive angle of attack along the whole span is developed lift by the wing. If it is big enough, the wing tip will be raised.

During the turn upwards especially the outer wing area is blown more from above. The angle of attack there is getting smaller or even negative. For a strong power development this is not ideal. To compensate this effect, the wing will be twisted beginning from the wing root. The angle of incidence at the wing tip will be increased so that the angle of attack is positive also during rotary motion of the wing. Thereby it is advantageous a permanent adjustment to the rotating speed.

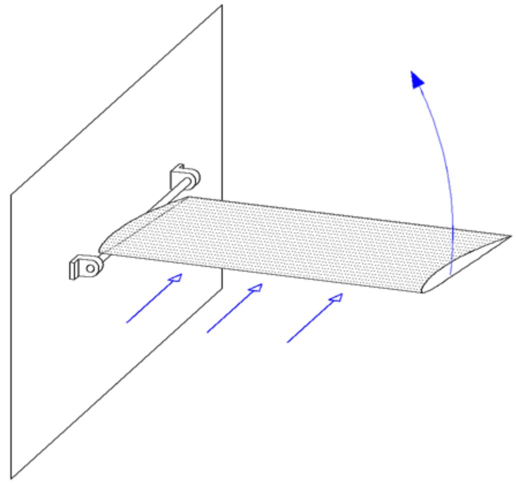

Figure 2. A wing at the root rotatable mounted in a wind tunnel

One can now also arrange the wing rotatable freely. Than it will not only beat up, but rotate continuously around its axis. The rotating wing can drive a generator. It then works like the blade of a wind turbine and emits energy. To remember:

lift force [N] x pressure point distance from the wing root [m] = torque [Nm]

torque [Nm] x angle of rotation [rad] = work or energy [Nm]

The energy which the wing gives up to the generator is detracted before by an additional drag from the air flow. In the wind tunnel the airflow is decelerated. In contrast, in free flight it is the mass of the aircraft whose speed is reduced.

The upstroke of a flapping wing can function in the same manner. However, it is known that the downstroke works like a propeller. That now the upstroke shall acts as a wind turbine, therefore initially seems to be paradoxical. There the upstroke would negate the effect of the downstroke. However, from the following Figure 3 you can easily read that on upstroke in the range with positive angle of attack can be generated lift and on negative angle of attack also thrust. Both are positive properties. So it depends on the details. The big advantage of an upstroke with the function as a wind turbine is the lift which is developed thereby. If no lift is generated on upstroke, the whole lift of the aircraft must be generated only on downstroke.

When applying the designations of the force in Figure 3 there is a special characteristic. It appears in particular because "thrust" and "additional drag" named the same physical quantity. It is always the same component of the lift force. However, it changes at the zero crossing of upstroke to downstroke or on upstroke along the span not its sign but its designation. This is misleading and it comes to misunderstandings about the cause of the additional drag. It is nothing more than thrust against the direction of flight. But the change of designation is used by biologists in birds, on modelling in ornithopters and also here. However, it is necessary to term this physical quantity at least in calculations throughout as thrust and then to accept the change of sign.

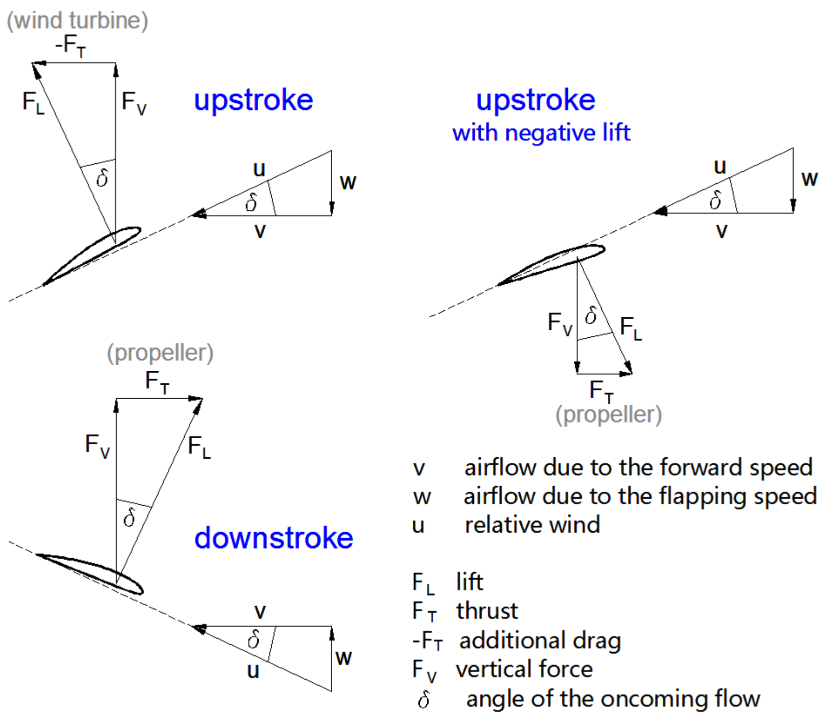

Figure 3. Forces on the flapping wing in the outboard wing area
This is an illustration without airfoil and induced drag.
One can also term the additional drag $-F_T$ during the upstroke with positive lift as operating or working drag of the wind turbine function.

To assess the effect of a force in flapping flight, besides their size there also must be considered the duration of their action. For this is formed the product of force and time.The result is commonly called force impulse.

force [N] x duration of action [s] = force impulse [Ns]

One can assume, in first approximation that the downstroke takes about half the time of a flapping period. When generating lift only during the downstroke thereby must develop a lift impulse sufficient for the whole flapping period. So it must be as large as the lift force in gliding flight during the length of a whole flapping period. Because of the short duration of action this requires an average lift of the downstroke, twice as large as that of the gliding flight.

average lift on downstroke [N] = 2 x lift in gliding flight [N]

average lift on downstroke [N] x half flapping period [s] = lift in gliding flight [N] x whole flapping period [s]

The maximum of the lift in the middle of the downstroke is then even considerably more than twice as large. As a rule, the wing area must be about doubled in comparison with a normally loaded wing in gliding flight. Also for strength reasons therewith the wing weight increases accordingly. In gliding flight then you can fly only with low wing loading and hence only with low speed, at last with optimal angle of attack. While maintaining the wingspan there is halved the aspect ratio with corresponding high induced drag on downstroke. The airfoil drag is doubled. Because of the larger drags a higher flapping frequency is necessary for thrust compensation. During the upstroke you must, so to speak, haul along the strong enlarged wing area, although the lift generation thereby is significantly smaller than in the gliding flight. Moreover, by the large lift on downstroke the torque of the gear increases, too. Also the motor current and the electronic controller are affected of it. An alternative is the halving of the flight weight. So on upstroke to produce no or only very little lift has a whole series of considerably disadvantages.

Another option to strengthen the lift on downstroke is to increase the airspeed. But that likewise increases the airfoil drag and this continues to require a high driving performance on downstroke. In this case there is also affected the parasitic drag from the enhancement of the drags. Therefore it is very useful to relieve the downstroke as far as possible and also to generate strong lift on upstroke. Moreover, then get smaller the vertical oscillation of the fuselage.

While maintaining the lift distribution and the duration of the flapping period lift and thrust also changed on modifying the cycle time ratio of upstroke to downstroke. In shortening the downstroke the total thrust of up and down stroke get smaller and the total lift increased (see Handbook[2], chapter 8.5 and Figure 9.6). As will be described in the following however, the decreasing thrust already caused enough problems in the improvement of the efficiency. Therefore the variation of cycle time ratio is not further investigated here. With high thrust models however, it is a possibility to increase the lift. The strength of thrust is also affected by the flapping frequency. But also that is not the issue here. It is generally assumed here from a mean constant value[A] of the flapping frequency.

Birds are often admired because of their lightweight construction. This applies for example to hollow bones, feather-weight feathers, air sacs in the body and for various other biological features. In contrast, birds as a whole have a relatively high weight, at least from the point of view of an aero modeler. Current ornithopters, however, are usually very light. In the following Table 1 are specified some examples.

Ornithopter	wing span [m]	weight [kg]	wing loading [N/m²]	**Birds** [3]	wing span [m]	weight [kg]	wing loading [N/m²]
Cybird	0,9	0,29	16	Carrion Crow	0,8	0,6	46
Park Hawk 1	1,2	0,43	17	Peregrine Falcon	1,1	0,8	62
Slow Hawk 2	1,2	0,44	13	Herring Gull	1,4	1,1	52
SmartBird	2,0	0,45	9	White Stork	1,9	3,1	61
				Greylag Goose	1,6	3,2	115
				Mute Swan	2,4	11,8	170

Table 1. Comparison of the flight weights

Although to days ornithopters have very powerful drives, nevertheless they hardly tolerate a payload. A fuselage fairing to protect the drive mechanism sometimes is too heavy for them. This lift weakness will be counteracting somewhat by large wing root depth (similar to Flying Foxes or bats) and by strong erecting of the fuselage (see Figure 4). Thereby, will be increased particularly the angle of attack in the wing area close to the fuselage and so the lift there. In addition, by the inclination of the stroke plane the thrust will be directed a little upwards at the same time and therewith replaced missing lift. The power requirement of this way of flying, however, is considerable.

[A] The mean value of the flapping frequency f_m [Hz] of birds is about

$$f_m = e^{\log \frac{10}{m_b}}$$

with the mass of the bird m_b [kg], see

Hertel Heinrich. Structure-form-movement. New York, Reinhold, 1966

The greater the displacement of the lift, the greater the thrust change with variation of the flapping period.

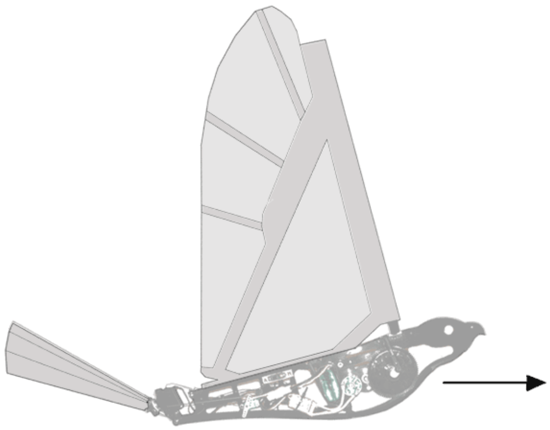

Figure 4.
Ornithopter in level flight

Thus the arrangement of the wing upstroke has certainly a substantial influence on the power consumption and the load-carrying capacity of ornithopters.

2. Operating modes on wing upstroke

A basic upstroke lift distribution is shown in the following Figure 5. In the area close to the fuselage the lift is positive. With its motion in the direction of the lift force the flapping wing works there as a wind turbine. Thereby generates an additional drag against the flight direction. In the remaining area near the wing tip the lift is negative. In this way the flapping wing acts there like a propeller and generates thrust.

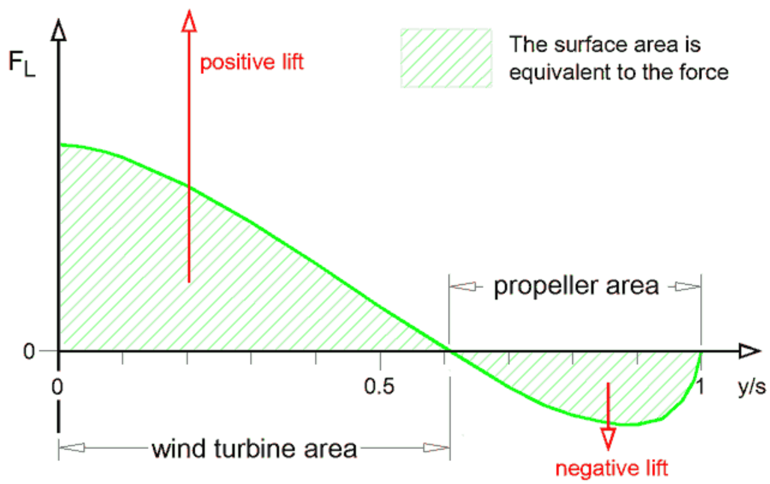

Figure 5. Lift distribution on upstroke with balanced torque and balanced thrust
It marks the boundary between predominantly propeller operating mode and predominantly wind turbine operating mode.
The pressure point of this distribution lies directly on the wing root.
Calculated with the computer program "Orni 1"[4]

F_L = lift force
y/s = relative half span

The flapping motion near the wing tip is significantly larger than near the wing root. Accordingly, also behaves in each case the performed work along the half span. The smaller area with negative lift near the wing tip here performs the same work during rotary motion as the larger area with positive lift near the wing root. Additional drag and thrust in this special case just equates each other. Also the opposite torques of positive lift and negative lift are exactly the same. Thus, the wing can be moved upwards without an external force.

From the graph you can read an important generally applicable principle for flapping wings. Wing sections with the lift force in the direction of motion operate as a wind turbine and wing sections with the lift force against the direction of motion operate as a propeller. At the same time, one of the ways is recognizable in this picture how can be used the wind turbine energy which is generated in the inner wing area. It can be used directly for thrust generation in the outer wing area. The inner wing area thereby drives the outer wing area in upstroke direction. This is probably the most important method for recovering of wind turbine energy in flapping wing upstroke. It is certainly also be used by birds.

The somewhat surprising in this lift distribution is, that the without torque upward moving flapping wing is still producing some lift (27 % of the lift in gliding flight with elliptical distribution). The upward directed force of the wind turbine area is much bigger than the downward directed force of the propeller area. This confirms an important feature of the wing upstroke. Also at it can be generated lift without additional loss of energy.

For most current ornithopters it is basically difficult to generate significant lift during the upstroke. Their drive motor is in full operation not only on downstroke but also on up-stroke. That's about the way of flying of hummingbirds in stationary flight. Only the wing thereby can absorb the energy output of the motor. To develop an equal opposite force, the wing is constrained to work with a large propeller area also on upstroke. Indeed thereby is developed very much thrust but instead less lift. The lift distributions of ornithopters which are flying in this way and having a large angle of attack near the wing root then will look like about in the Figure 6.

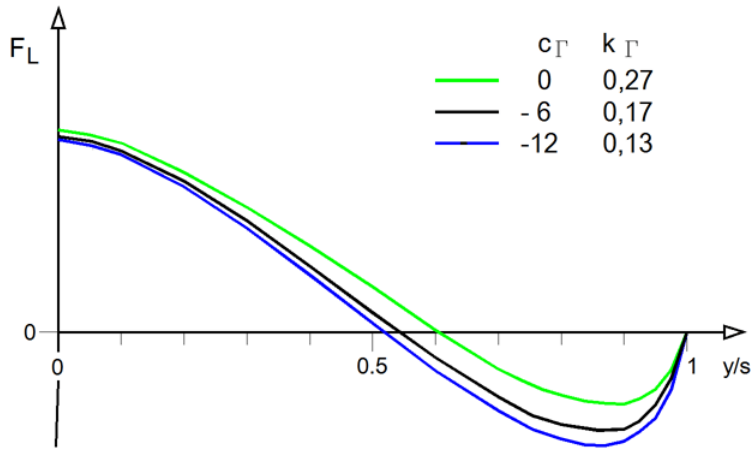

Figure 6. These are lift distributions for the upstroke in the propeller mode
For comparison is also shown the lift distribution with balanced torque, with circulation characteristic number „c-Gamma“ $c_\Gamma = 0$.
The circulation factor k_Γ (k- Gamma) describes the size of lift based on that of gliding flight.

F_L = lift force
y/s = relative half span

The areas with positive and negative lift are relative strongly developed and lies directly side by side. Thus the induced drag is large. The resulting total lift, however, is very small. Excess wind turbine energy is not available. On contrary, the thrust generation pre-dominates and is considerable on such an upstroke. But the airfoil in the outer wing area thereby must work during upstroke with strong negative and during the downstroke with strong positive angles of attack. This is almost only possible with membrane wings, because their airfoil form can be flexible cambered upward or downward.

The following Figure 7 shows some lift distributions for the upstroke with significant lift generation. They range from the lift distribution with balanced torque to a lift distribution with a throughout positive lift. Thus these lift distributions cover about the operating range of a wing upstroke in wind turbine mode.

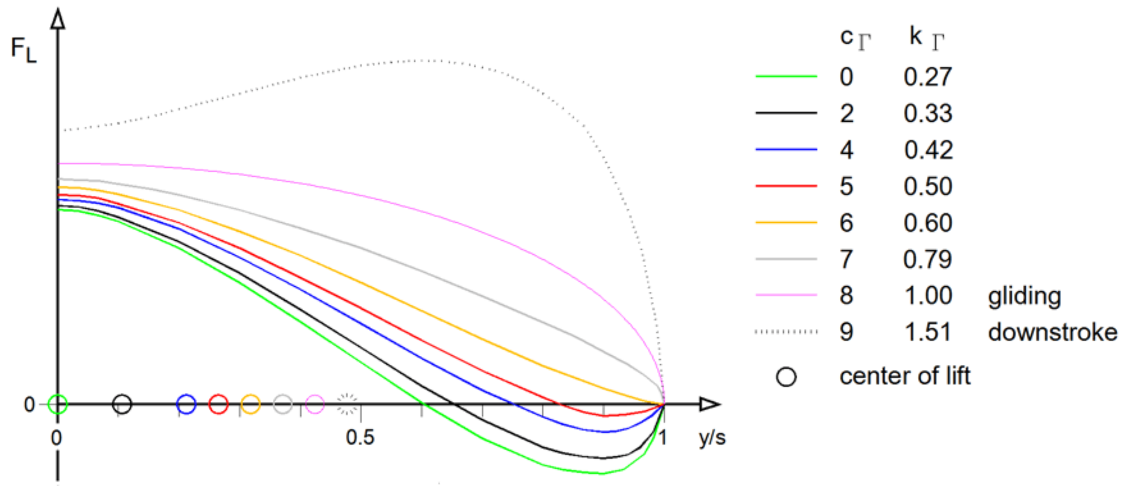

Figure 7. Various lift distributions for the upstroke in the wind turbine mode
For comparison also are shown the following lift distributions:
$c_\Gamma = 0$, with balanced torque
$c_\Gamma = 8$, as an example for the gliding flight
$c_\Gamma = 9$, as an example for the downstroke
The circulation factor k_Γ (k- Gamma) describes the size of lift based on that of gliding flight.

In this comparison of upstroke distributions the lift distribution with the circulation characteristic number $c_\Gamma = 5$ has the lowest induced drag. The length of its propeller area approximately equals to the free length of the primary feathers in large birds. This lift distribution also equates to those which was delineated by Otto Lilienthal (see following Figure 8). Admittedly, this has not been proven so far with technical measurement neither on birds nor on technical flapping wings.

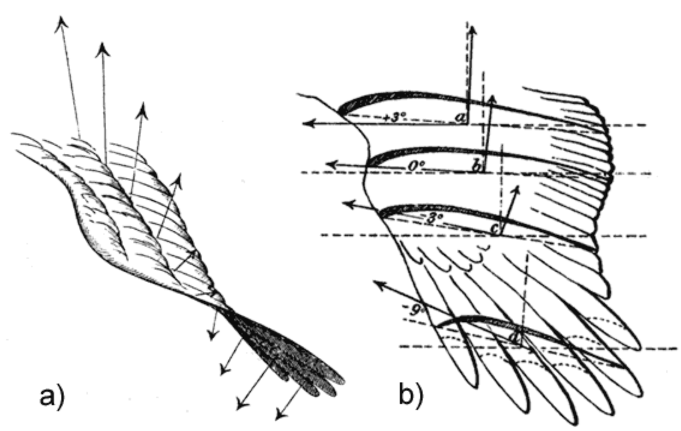

Figure 8. Two examples of lift distributions on wing upstroke by Otto Lilienthal[5] (1889)
In drawing "a" however, the forces near the wing root are directed too much forward.

If on upstroke the torque of the wind turbine area is not complete compensated by the opposed torque of the propeller area, the force balance must be performed somehow in another way. Otherwise, without counterforce the lift force cannot develop on the wing. One must look then for other applications of the excess wind turbine energy (see chapter 9).

3. Sinusoidal course

In the above Figure 7 only lift distributions of the upstroke are shown how they are in the middle of the stroke motion. In which way the transition between up- and downstroke can be archived, is not determined with it. But in general, the ornithopter theory assumes a temporally sinusoidal curve of the motions and the aerodynamic conditions. In the following Figure 9, the flapping motion of the wing is shown in the form of its stroke or angular velocity ω together with the respective stroke angle Φ. The change of the lift distribution takes place, at least with aeroelastic wing twisting, depending on the angular velocity. In its course are specified sample values of circulation characteristic numbers c_Γ at different times and below are shown the relevant distributions of lift in small format.

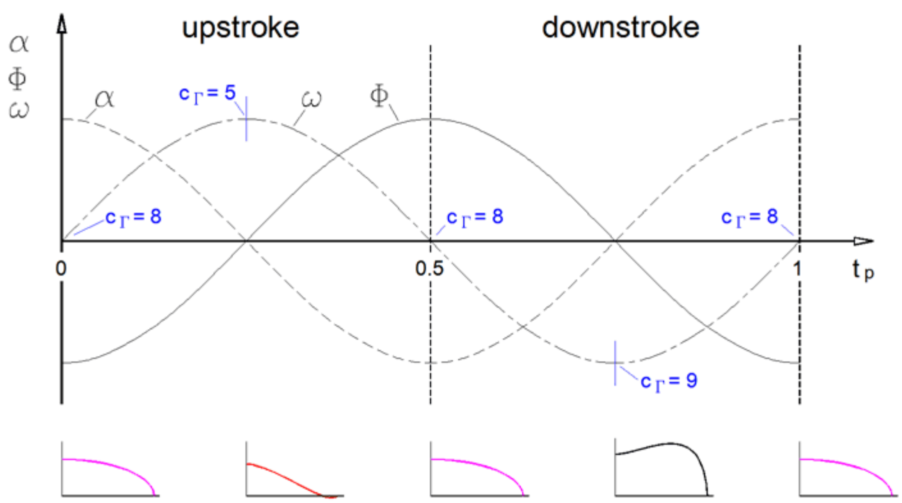

Figure 9. Basic, temporally sinusoidal course of the flapping wing motion
Φ stroke angle
ω angular velocity
α angular acceleration

One must, however, be aware that under these conditions the mentioned lift distributions of up- and downstroke (see for example Figure 7) are valid only for a very short moment in the middle of the stroke. In the remaining time, so for about 99 % of the flapping period, takes place a lift displacement between these forms of distribution - a slightly unusual thought. But from aerodynamic point of view, the always displacement of lift is the essential of the flapping flight. The specification of a "lift distribution for the upstroke" is actually misleading. But it will be needed for the description of the upstroke.

4. Size of lift only with wing twisting

In calculating program “Orni 1”[4] on a rectangular wing only twistings are calculated which arises during the stroke motion in flight by arbitrary lift distributions. Other wing motions are not included. Thereby with each displacement of the lift automatically changes as well its size. With the help of the circulation factor and its combination of shifting and resizing the angle of incidence at the wing root is kept constant. It is therefore only worked with the wing twisting.

In this method, the lift during its displacement towards the wing root becomes always smaller. Hence, thereby you should not displace the lift too far to the wing root on upstroke. However, then the additional drag is still relatively large. The changes become clear in the following Figure 10.

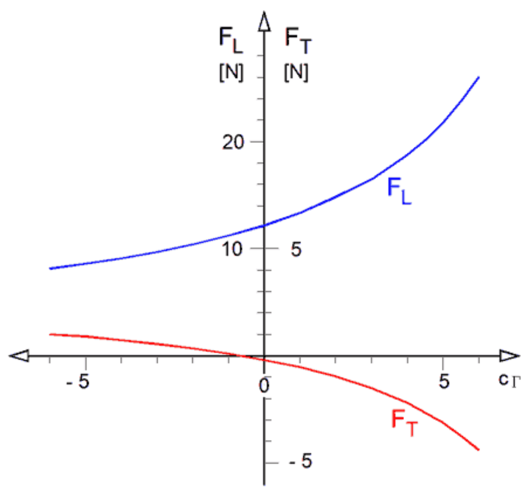

Figure 10. Course of lift force F_L and thrust force F_T on wing upstroke as a function of the circulation characteristic number c_Γ (c-Gamma) in an example of a rectangular wing. Calculated with the computer program “Orni 1”[4]

In the increasing concentration of lift in mid-span one can easily imagine that the cross-flow along the wing is getting always stronger. In the calculating program this will be largely balanced by the ever decreasing lift. The induced drag increases so only slightly. If one however, increased the lift on upstroke, the cross-flow or the induced drag becomes a problem. Birds apply as a countermeasure the bending of the hand wing. This then acts as a winglet or end-plate and reduces the wing tip vortex and the cross-flow. On ornithopters already may be helpful instead of a bending even a wing fence between arm and hand wing to reduce the cross-flow of the wings.

In attempt to increase the lift on upstroke I see the limit of the lift displacement about in the circulation characteristic number $c_{\Gamma} = 5$. The lift size is then still about 50% of the lift of an elliptical distribution (Figure 7). A further displacement towards wing root only by wing twisting does not make sense. This applies at least for a rectangular wing with a simple airfoil along the whole span. For ornithopters 50% of gliding lift on upstroke is certainly a quite passable value. But in this case achievable thrust is sufficient only for a level flight or a very gently inclined climb flight.

At increase of lift on upstroke, generally one must keep in mind also the lift on downstroke. It then can be smaller. Beside adjustment of the lift distribution for this is also suitable a lower flight velocity. At least in the first case this means less thrust.

5. Rotation of the wing root

5.1 Size of lift with rotation of the wing root

By rotating the wing root in the middle of the stroke one can further increase the lift generation by wing twisting on upstroke. In calculating program "Orni 1" thereto one must remove the link between displacement and resizing of the lift. This can be achieved by entering of appropriate values in the actually not designated as an input parameter "circulation factor" ($k_{\Gamma 1}$=0.5 to 1.2). The size of lift can selectively modify in this way. At the same time changes the angle of incidence at the wing root. But that only applies to the wing rotation with the maximum in the middle of the stroke. In slow motion shots of birds I could not recognize such a rotation so far in the past. Erich v. Holst[1] however has suggested it to equalize the lift.

In this way (e.g. with $c_{\Gamma 1} = 5$) one can increase the lift on upstroke so far till the lift coefficient reaches the maximum value of a simple airfoil on the wing root (see Figure 11). While maintaining the balance[B] of forces in a level flight with a rotation of about +5 degrees (only on upstroke, maximum in the middle of the upstroke) one reached about 77%

[B] Changed values for the balance of forces in the calculation program „Orni 1“: upstroke circulation characteristic number $c_{\Gamma 1} = 5.0$; upstroke circulation characteristic factor $k_{\Gamma 1} = 0.772$; downstroke circulation characteristic number $c_{\Gamma 2} = 8.975$; flight speed factor $k_V = 0.980$

of the lift in gliding flight. Compared to the process only with wing twisting this is significantly more. With a strong chambered airfoil near the wing root and / or large wing depth in this area, the lift can be increased further more. Not for nothing have birds in the arm wing section a strongly cambered profile.

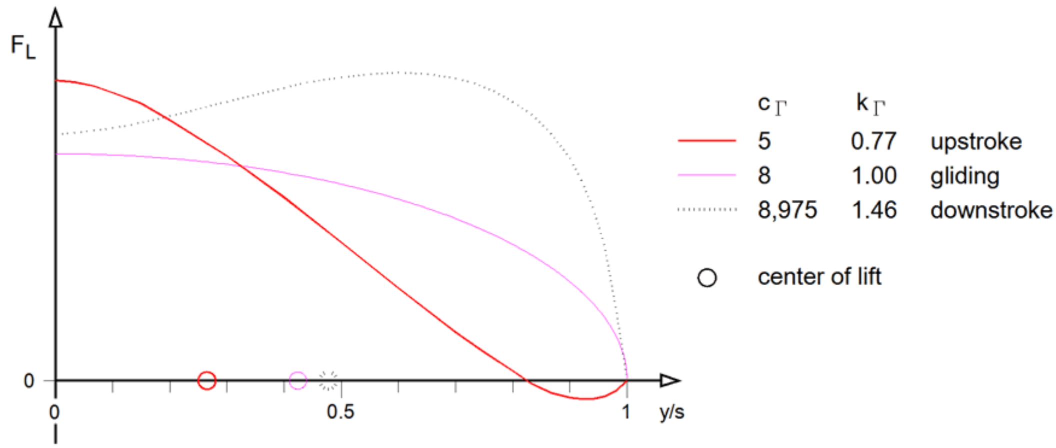

Figure 11. Distributions of lift forces F_L on upstroke, in $c_\Gamma = 5$ with rotation of the wing root

By the combination of wing twisting with the rotation of the wing root one can increase a little the lift on upstroke. But this only works with a moderate demand of thrust or with relatively high additional drag.

An increasing of the angle of attack at the wing root affects in wings with low torsional stiffness particularly in close range, so in the arm wing. Outside is eased slightly the angle of attack to the rising lift. But in the construction of the wing a rotation of the wing root always should be considered. The wing twisting on upstroke then can be smaller.

5.2 Lift in the stroke end positions

As a distinctive intermediate stage between up and downstroke particularly for calculations can still be specified a middle lift distribution. Therefore is suitable the lift distribution of gliding flight. It shall apply for both stroke end positions. This seems to be plausible, because at least a straight flapping wing of an ornithopter comes to a standstill between the two stroke directions short-time. At the same time the gliding situation is a good guideline for assessing the changes on the flapping wing in the diagrams. But the gliding flight situation in the end position of ornithopters and especially in birds is not always correctly described with an elliptical lift distribution. This is only a first approximation.

The wing twisting of birds by the anatomy is fixed in the glide position in the outstretched wing position (see chapter 7). If with the downstroke motion varies the direction of flow, however, the wing twisting gives way in an elastic manner. Also with muscle strength are still possible small changes in the twist. But in the upper final stroke position in the short moment of the wing standstill when the hand wing has reached the stretched wing position, as a rule, the lift distribution of gliding is probably also present in birds.

In the lower end position, the situation in birds is not so quite clear. The pivoting and bending motions of the hand wing have usually already set in there. But one can assume that shortly before reaching the lower stroke end position, the wings are still stretched and the downstroke motion is already very small. Also in this case is then approximately given the glide situation. Thus also in birds one can approximately describe the wing end position with the gliding condition.

For the transition between the two stroke cycles it is interesting that on large birds in cruising flight sometimes can be seen a slight pendulum motion of the angle of attack by the bird's body. Its lift he generated together with the tail thereby is varied. Because the wing roots on both sides of the body follow this pendulum motion, also synchronously is changing their angle of attack. Approximately, the minimum angle of attack is at the upper and the maximum at the lower stroke end position.

The following Figure 12 was made from a slow motion picture of a Greylag Goose (Greylag Goose Slow Motion Flock Flying Over Lake, by Lloyd Buck[6], two images, about on playtime 2:12, mirrored). The red image shows the bird in the upper and the blue image in the lower stroke end position. Both images were aligned with each other to the eye of the Greylag Goose. As you can see, head and tail keep on practically the same relative level, while the neck and the chest moves clearly up and down. Consequently, the body’s angle of attack is changing.

When searching for changes in the angle of attack at the wing root therefore one should not look for motions of the wing’s trailing edge compared to the bird's body. There practically don’t take place a relative motion. Also the position of the leading edge of the wing relative to the bird's body does not change. One must try to determine the centreline of the bird body. But videos exactly from the front would be the best. On those you can direct compare the height of the leading and trailing edge of the wing (see Figure 13 and 20 and the animations of flying birds based on films by A. Piskorsch [7]). To estimate the centre line of the bird body is only a makeshift.

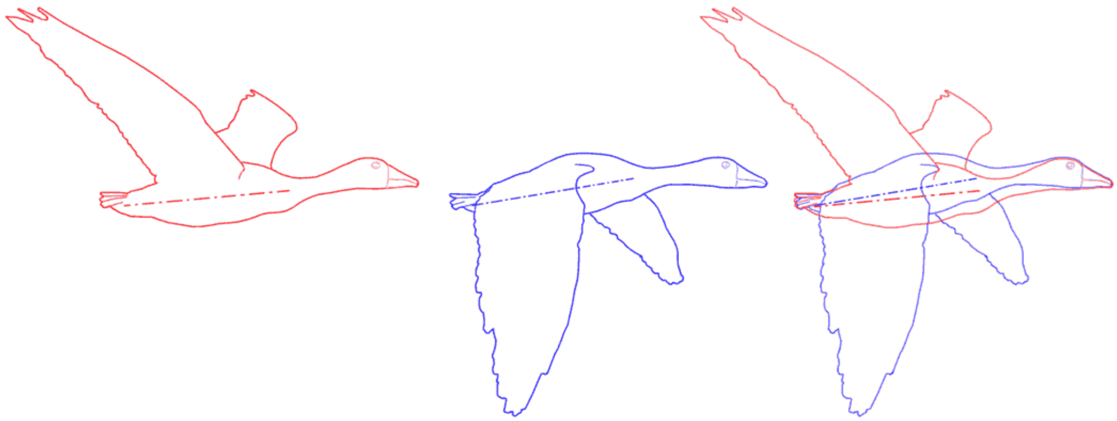

Figure 12. Nodding or swinging of the body of a Greylag Goose with illustration of the body axes.

The increased angle of attack at the beginning of the upstroke leads to a greater lift at the wing root. This is an indication that birds have already shifted for the upstroke a substantial part of lift of the downstroke to the wing root at this time. At this point, birds often even fold together the hand wing. Conversely, the decreasing of lift at the wing root in the upper stroke end position allows us to conclude, that in mid-span a substantial part of the upstroke lift has been dismantled and displaced toward the wing tip, at least till to the arm wing. In both cases, the corresponding displacements of lift along the wing must be performed there by modifications of the angle of attack.

The oscillation of the bird body is generated by forward and rearward displacement of the lift centre compared to the centre of gravity. This occurs partly automatically. As is known, on cambered airfoils the centre of pressure with large angle of attack moves forward and with reduces angle of attack toward the rear. In addition are playing a role the wing sweep or the pivoting of the hand wings backward (see chapter 7), the inclination of the stroke plane (see chapter 8) and the moment of inertia of the fuselage. Beside also play a part the forward or rearward directed forces near the wing tip in the range of the stroke end positions (see handbook "How Ornithopters Fly"[2], Figure A 14, in German). Therefore body oscillation is a very complex process.

The nodding motion comes about to a standstill in the end positions. Accordingly the nodding speed is greatest in stroke middle. In this way as a result of the nodding motion downward the upstream flow angle will be enlarged at the leading edge of the wing during the upstroke. Thus, the lift is somewhat kept high even still in this time range. On downstroke that reversed. Both are in terms of lift displacement assessed as positive.

5.3 Wing motions of a swan

Something different looks the rotation of the wing root if one analyzed the images of a swan from a movie clip by A. Piskorsch[7] (see following Figures 14 and 15). Unfortunately, the image material is slightly blurred and the result corresponding inexactly.

Figure 13. Swan from the front, based on a movie clip by A. Piskorsch[7]

In following Figure 14 the end of the upstroke was set on the beginning of the downstroke motion of the arm wing (course of stroke angle Φ). The upstroke motion of the hand wing has practically ended there (course of bending δ). In this figure show increase and decrease of the angle of attack α very well the temporal sequence of lift displacement between wing and mid-span.

The maximum angle of attack in this case is not present as in the goose in the lower stroke position, but in the first half of the upstroke. It is been built up together with the bending δ of the hand wing in the early stage of the upstroke motion. The increase already starts towards the end of the downstroke. A distinct minimum as in the goose in Figure 12 cannot be seen in the upper stroke position. In this wing position is more an angle of attack as it might be present also in gliding flight. It is there almost constant for a longer time. Changes of the angle of attack at the wing root on an elastic twistable wing affects especially in close range, thus on the arm wing. But if one look at this low even though over a longer time relatively constant angle of attack as a minimum at the same time, the two mentioned cases of goose and swan are not so different.

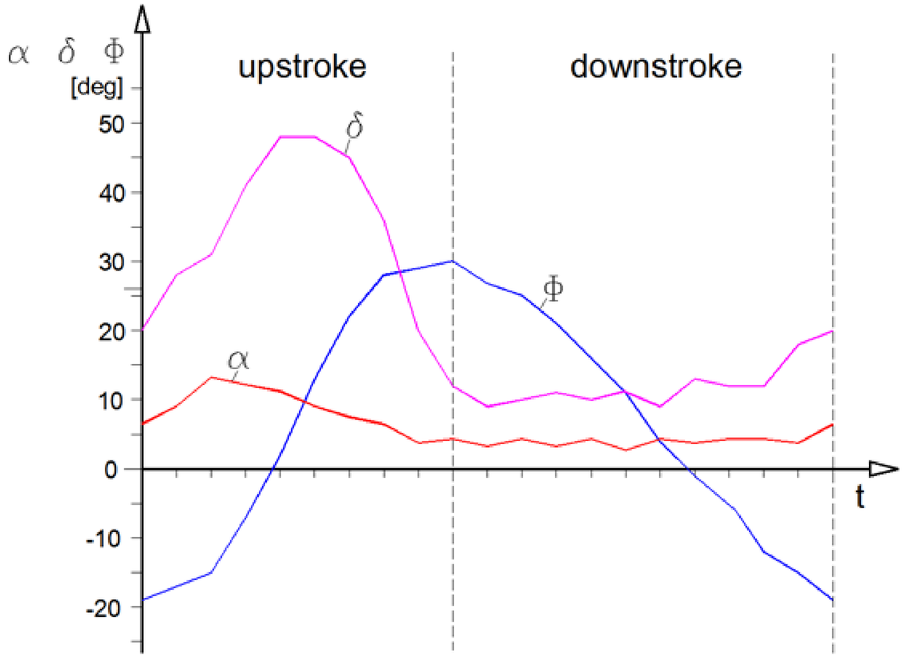

Figure 14. Wing positions during a flapping period of a swan in cruise flight based on a movie clip by A. Piskorsch[7]

Φ stroke angle of the arm wing compared to the horizontal

δ bending of the hand wing compared to the arm wing

α angle of attack[C] on the wing root or bird's body

In the Figure 14 the angle of attack is especially high at the wing root during the upward motion of the arm wing. During this time, the lift is mainly generated only in the arm wing, thus in a partial length of the wing. Therefore, the rotation of the wing root can also be regarded as method to keep the lift constant. However, the increased lift works in wind turbine mode. But because the strong concentration of the lift near the body or of the small lever arm the performance is low. Thus, the additional drag remains small despite of large lift.

The bending δ of the hand wing compared to the arm wing does not go back to zero on downstroke. This is due to the type of image evaluation. The wing of the swan is curved downward also on downstroke along the whole half span. Arm and hand wing have been each replaced by straight lines. In this way the bending of about 10 degrees remains on downstroke. One ought actually, to move the whole course of the bending in the diagram by 10 degrees downward. The maximum angle of bending is then only 40 degrees.

[C] Strictly speaking, you have to add a few degrees to this angle of attack, since the footage was taken from a bridge, so from above.

It is remarkable that the bending of the hand wing already started before the downstroke of the arm wing has ended. The reason for this is partly the decrease of the lift forces in the outboard wing area. The hand wing thereby springs elastically a few degrees downward. In addition it can also not be fully ruled out that the bending of the hand wing, at least at the beginning is done by muscle power. But due to the weak muscles to move the hand wing[11] this is very unlikely.

After its upstroke motion of the arm wing takes a break. It is a kind of transitional phase. Only the hand wing is still moving upwards. At the end, in the outstretched hand wing position the wing twist is mechanically fixed (see chapter 7). Without downstroke motion of the whole wing it is then like in gliding flight. In this way in the transition phase with the relatively powerless upstroke motion of the hand wing is displaced the lift to the outer wing area and so prepared for the downstroke.

5.4 Phase shift of the lift displacement on the wing root

Considering only the stroke angle Φ and the size of the lift in form of the angle of attack α, one has the impression that both variables do not behave according to the normal Figure 9. They seem to run nearly independently (see following Figure 15). But the offset times of distinctive basic parameters of these distributions pointed all in the same direction. The start of the enlargement of lift runs ahead of the start of the upstroke motion of the arm wing by the time span $\varphi\ ^{*})$. The maximum of the lift is by the time φ before the middle of the upstroke motion. And the end of the lift enlargement is advanced at about the same time $\varphi^{**})$. One therefore can speak on upstroke of a phase shift φ between stroke motion and the lift displacement on the wing root.

At the end of the upstroke the arm wing takes a waiting time. Also, it lasts hardly longer than the time period φ. In this transition phase, the lift is moved into the outer wing area and thus the lift displacement and the stroke velocity will be brought again in their normal phase position to each other.

The buildup of lift in mid-span can be described rather concretely with reference to the rotation of the wing root. But at the same time should be effected after the normal previous theory a reduction of lift in the outboard wing area. Instead one can see in the individual images of the swan that the wing bending starts towards the end of the downstroke, even during the primary feathers are slightly curved upwards. In the lower stroke end position therefore is existent distinctive lift at the wing root and in the outer wing area at the same time. This is still a bit unusual. In addition, then apparently is required the application of muscular work.

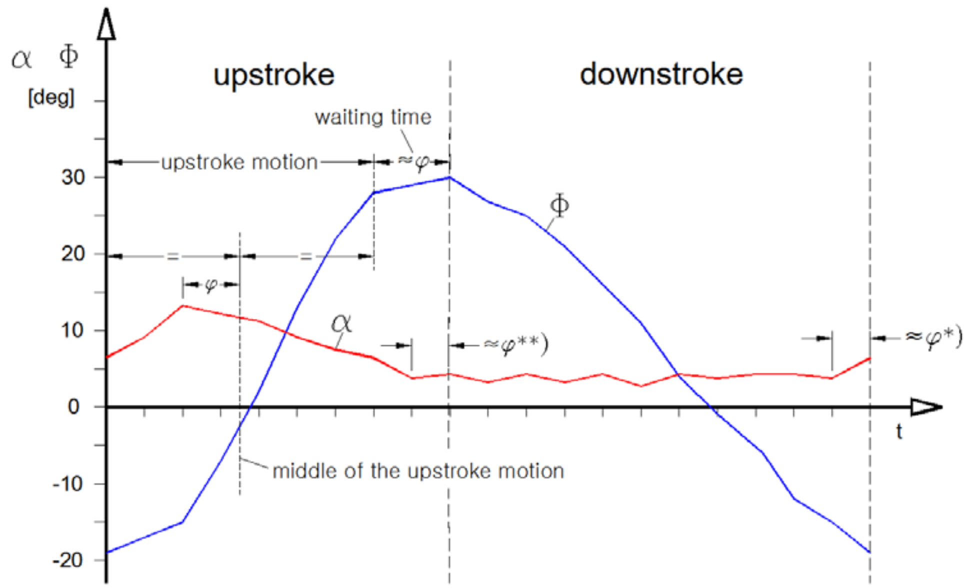

Figure 15. Phase shift φ between the lift displacement at the wing root and the stroke angle of the arm wing

Φ stroke angle of the arm wing compared to the horizontal

α angle of attack on the wing root or of bird's body

$*)$ by φ earlier beginning of lift displacement

$**)$ by φ earlier ending of lift displacement

When assessing the phase shift, is taken into consideration that in the underlying diagram (Figure 15) somewhat arbitrary for the different time points were used the pictures with its time intervals prescribed by the movie recording. In addition, there is only this one slightly blurred image material for the detection of the phase shift.

It looks as if the phase shift of the lift displacement is practiced by the Swan to achieve a big lift in the lower stroke end position. The lift is indeed build up early in the mid-span, but only delay reduced in the outboard wing area. Thus, the lift can be concentrated in the mid-span when the hand wing is still not bended. The speed of the upstroke motion thereby is still low. In the range of the upper stroke end position the lift is mainly displaced during the waiting time of the arm wing in the outboard wing area, so virtually with no upstroke motion of the arm wing. In this both time segments of the upstroke therefore is generated considerable lift with very little additional drag.

The decrease of lift in the outer wing area in the lower stroke end position takes a relatively long time. The upstroke still begins, while the primary feathers are slightly bent upwards. Nevertheless, it is possible that during the upstroke at the time of the maximum lift in the mid-span (Figure 15), much of the lift has already been displaced along the wing in the direction of the wing root. Thereby then there is already negative or at least very little lift in the outer bended wing area at this time. In this way the bending of the hand wing is supported by the change in its aerodynamic forces at an early stage.

5.5 Compensation of the inertial force of the wing

One possible reason for the above-mentioned phase shift of the lift displacement is the compensation of the inertial force of the wing. It results, because the change in the stroke or angular velocity of the wing mass. During the braking of the mass the inertial force acts in, and when accelerating against the direction of motion. The maximum inertial force is directly in the end position (see the course of acceleration α_B in Figure 9).

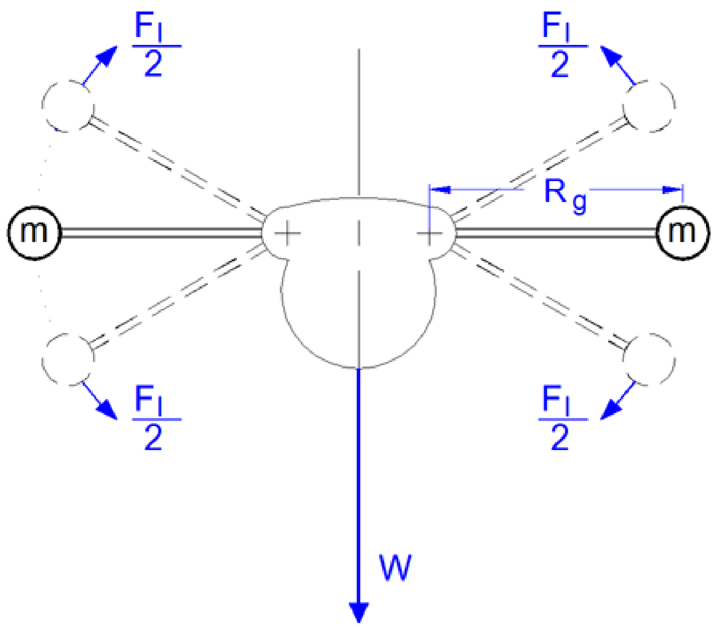

Figure 16. Concentration of the wing mass m on the radius of gyration R_g and its inertial force F_I in the end positions. The radius of gyration of the flapping wing is the distance from the axis where its mass is concentrated while maintaining the moment of inertia.

In the range of the upper end position, the inertial force at the end of the wing upstroke acts as a lift increase. The aerodynamic lift may or may not be adapted accordingly. The additional lift does not damage. But the bending moment because inertia should be taken into account in the material strength of the wing.

One possibility for reducing the inertial force is the articulated connection of arm and hand wing. As a result of the short partial lengths of the arm and hand wing, their radius of gyration and their masses are correspondingly smaller. Both together have a very strong influence on the moment of inertia of both wing parts. During the acceleration process of the arm wing, indeed you cannot completely neglect the mass of the hand wing hanging on it. Nevertheless, it remains a significant reduction of the moment of inertia of the flapping wing. The two wing sections also do not reach the upper end position at the same time, but only successively.

Contrariwise, the force of inertia on the radius of gyration acts as an additional weight in the range of the lower end position. This is only true, however, if the wing mass is braked by the drive mechanism, thus out of inside the ornithopter. If, on the other hand, braking takes place from the outside, thus by the aerodynamic lift on the wing, then is generated no additional weight. It is therefore very advantageous to compensate the inertial forces in the range of the lower stroke end position by lift. However, this must be sufficiently large and accordingly verified.

The percentage of the maximum inertial force of the Ornithopter in the "Orni 1"[4] computer program is ± 70% of the model weight. The lift in the magnitude of the gliding flight in the end position, therefore, is sufficient for a sinusoidal motion sequence in order to break the wing in the lower end position without "weight increase". The inertial force is relative large in this case. However, it is calculated with a constant weight distribution along the whole wing. Many flapping wing structures will have a smaller distance to the center of gravity. However, it is not easy to determine the moment of inertia which is required for the calculation. A proposal for practice is made in the manual[2], chapter 5.6[D].

In birds, the moment of inertia is clearly smaller than in the case of ornithopters, because of the small distance between the shoulder joint of the wing and the smaller wing weight. Nevertheless, it may come to noticeable inertial forces. Iilluminative to this is the analysis of the flight of a Dun Crow in Figure 17 by Hans Oehme[8]. The position of the wing tips during downstroke shows that this is not temporal sinusoidal. The stroke velocity remains

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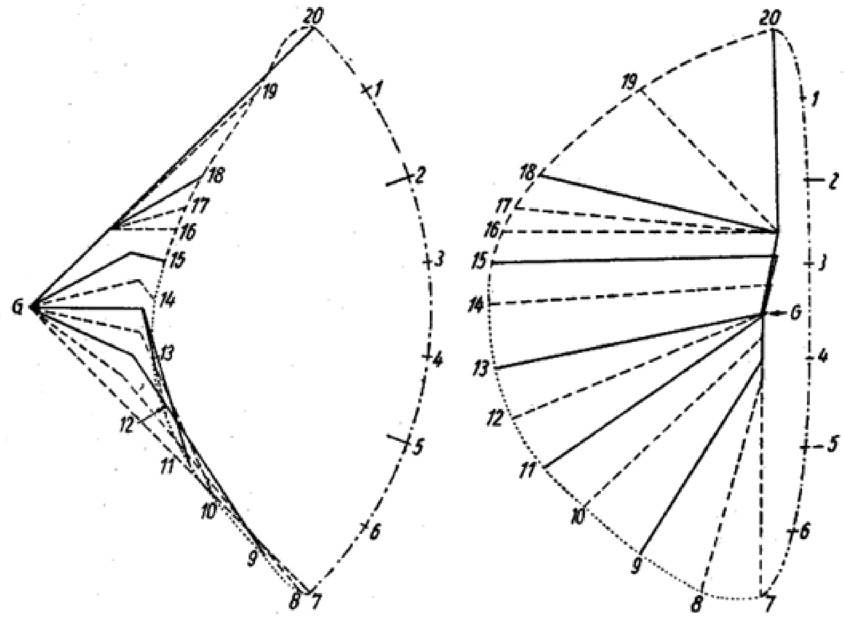
[D] Warning! The equation 5.12 in the manual it should read $J_F = \frac{m_F}{3} \cdot \left(\frac{b}{2}\right)^2$

The same error was also corrected in the computer program "Orni 1", version 4.0 and also supplemented the calculation of the inertial force.

almost constant during the whole downstroke. Only when approaching the lower end position, approximately starting from the position 6, does a deceleration start which already ends in the positions 7.



rear view side view

Figure 17. Diagram of the wing motion during a wing beat of a Dun Crow, with the shoulder joint G and the trajectory of the wing tip, from a movie in slow motion by Hans Oheme8.

A constant velocity of downstroke has the advantage compared to the sinusoidal course that the strong thrust and the large lift remain for a longer time. However, when the braking time and braking distance are shortened, the inertial force increases. In order to illustrate the increase, the description of the acceleration work for the wing mass is helpful. At the same initial conditions, the acceleration work for reaching a certain velocity is always the same.

$$W = F \cdot s$$

W	work of acceleration [Nm]
F	force of acceleration for overcoming the inertial force [N]
s	distance of acceleration [m]

Thus, as the distance of acceleration becomes smaller, the force of acceleration increases. If, for example, the angle or the distance for braking the wing mass is reduced to one-fifth, the inertial force increases to five-fold, at least with constant acceleration. Nevertheless, it is unlikely that, in this example, the lift of gliding flight of the end position for birds is no longer sufficient for breaking of the wing. In the case of ornithopters with shortened braking distance of the flapping wing, however, a check is generally recommended.

The effect of the inertial force can also be played on yourself. To do this, you place yourself on a bathroom scale, which should have an analogue display, if possible, and beats up and downwards with your arms. On the display of the scale then you can metering the described changes of your own weight.

5.6 Rotation of the wing root on ornithopters

For ornithopters it will not be easy to copy the nodding motion of the body. But with a long lever arm of the tail it is probably anyway better to work first with a rotation of the wing root related to the fuselage. But in which period the rotation of the wing root should be increased. At least in the case of straight flapping wings, the task is not necessary to initiate a bending (see chapter 6.2).

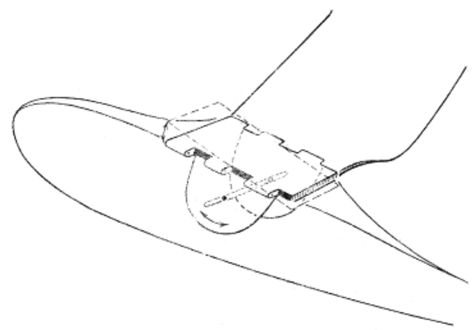


Figure 18. Suggestion for construction of a wing root rotation by Karl Herzog[9], from his series of articles „Der Schwingenflug in der Natur und in der Technik", nov. 1963

The swan data in Figure 14 and 15 as well as the pictorial illustration of the Greylag Goose in Figure 12 are only single cases of not closely described flight situations at any one bird species. So it is still unclear what temporal course of the angle of attack at the wing root under which conditions is more suitable. As long as there are no measurements from a wind tunnel, one must probably approach to the optimum by means of experiments. However, the course of the angle of attack α in Figure 15 is certainly a good point of reference for its size and the timing. The effects of the rotation of the wing root to the size of the wing twisting during upstroke, however, has to be considered in the construction of the flapping wing. The wing twisting can become smaller in this case.

In the ornithopters EV1 to EV5[10] I also used a rotation of the wing root (about ± 3 degrees). In the middle of upstroke was existent the maximum and in the middle of the downstroke the minimum of the angle of attack. The temporal course was sinusoidal. According to today's knowledge it was wrong to use a rotation of the wing root during downstroke.

6. Bending of the hand wing downward

6.1 Benefit of the bending

The advantage of a small moment of inertia of the flapping wing due to the bending has already been described in chapter 5.5. In cruise flight of birds the bending of the hand wing downward indeed remains relatively small. However, in the case of a large thrust requirement with a correspondingly large bending, it also offers advantages for thrust and lift. On upstroke the approaching flow at the hand wing happens more from above. Thereby can arise there negative lift. Because the hand wing with bending gives way with its motion downward, the negative lift is not so large. This is a first advantage of the wing bending.

Together with the bending changes the direction of the lift force on the hand wing. Thereby the forces on both wing sides of the bird balanced partially each other. The effective lift in the vertical direction thereby decreases (see Figure 19). With negative lift this is advantageous, with positive lift disadvantageous.

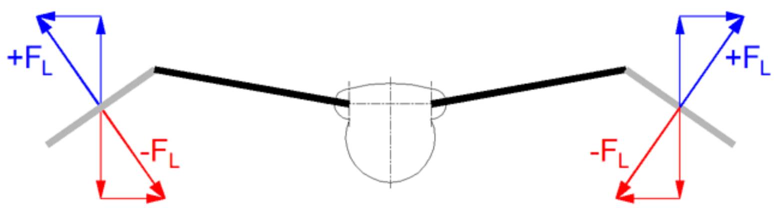


Figure 19. Direction of the lift forcees with wing bending on hand wing.
blue with positive lift
red with negative lift

The lift in the arm wing area is kept together by the end plate function of the hand wing. Thus the bending helps on the concentration of the lift in mid-span and therewith on the generation of thrust. But this only being worthwhile if there is actually high lift. Without strong lift in the area of the arm wing and without strong lift differences along the half span a strong bending is less reasonable. When the bending is used, the lift can be shifted somewhat further than with $c_\Gamma = 5$ to the wing root (see Figure 7).

In bending of the hand wing, its center of gravity from the stroke bearing of the wing becomes smaller. This also applies to its center of lift. Together with the above-mentioned reduction of the lift effect, this affects to the wind turbine function of the flapping wing. Its influence decreases. This also applies to the inertial force of the wing in the upper end position (see chapter 5.5). As a result, dwindle the necessity to use energy storage devices (chapter 9) when bending the hand wing.

6.2 Temporal sequence of the bending

A good overview about the beginning of the bending of the hand wing is shown in Figure 20. It shows the wing in the lower end position on the left side and the wing quite a while after the beginning of the arm wing upstroke on the right side. The wing tips in Fig. b are still slightly bent upwards.

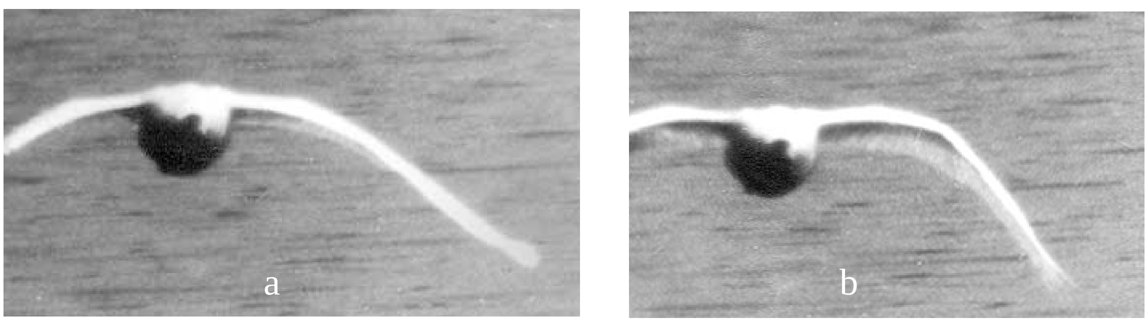


Figure 20. Beginning of the bending of the hand wing by lift, from a series of pictures by A.Piskorsch[7]

Such a motion of the arm wing may occur by itself on articulated arm and hand wings. Therefore, only a strong lift must exist in the arm wing area (for example like about with $c_\Gamma = 6$ and $c_\Gamma = 7$ in Figure 7). A considerably smaller lift in the area of the hand wing does barely impair this method. On the contrary, the hand wing tends to rotated by the upward motion of the arm wing about its center of gravity. In doing so, even it generates a little thrust on the wing tip. An involvement of muscle strength in the process is rather unlikely. In birds, the requirement to initiate the wing bending is, in addition to the lift generation, certainly an important reason for the early enlargement of the lift on the wing root.

On upstroke with a bending of the hand wing it is clear that the arm wing reached the upper stroke end position sooner than the hand wing. In slow motion videos of large birds then can be seen that the arm wing is waiting at the top until the hand wing has nearly reached about the stretched wing position (see e.g. Figure 15).

The delay of the arm wing in the upper stroke end position, with the contained upward motion of the hand wing and the lift displacement, is part of the transition from the up to the downstroke. Without this delay, the bending may include a very high mechanical load.

On the left side of the following Figure 21 is shown the motion sequence of the hand wing in birds. In that the hand wing moves upwards, as shown in position 1. The arm wing goes ahead of the hand wing and reaches in the position 2 the upper stroke end position. Subsequently, the arm wing remains in this position and is waiting until also the hand wing has reached the upper end position 3. In this time by changes of the angle of attack as a result of the hand wing motion lift will be shifted in the outboard wing area. With the stretched wing position then starts the downstroke with full thrust generation.

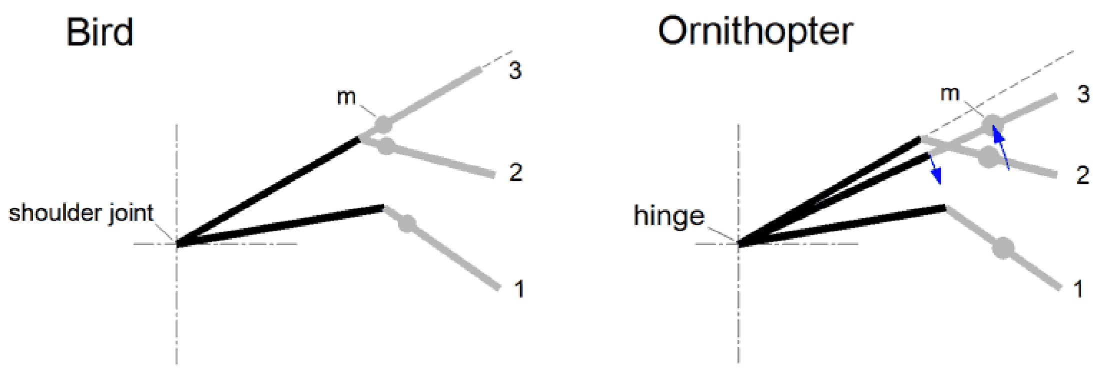


Figure 21. Comparison of the motion sequence of the hand wing in the range of the upper stroke end position.

In current ornithopter suggestions the drive generally is not stopped on reaching of the upper stroke end position. Thus, the arm wing does not wait until the hand wing is at the top. In addition, in contrast to the bird's wing the centre of gravity of the hand wing is located not so close to the wrist. This results in the following scenario, shown on the right side of the Figure 21.

The hand wing moves upward as shown in position 1. The arm wing is going ahead of the hand wing and reaches in position 2 the upper stroke end position. The drive immediately drives the arm wing downwards. But the hand wing is still in upward motion. It reached the stretched wing position in the position 3 and strikes hard there with its opposite motion against the end stop of its joint. At the same time the stopped mass of the hand wing is a very sudden obstacle to the downstroke motion of the whole wing. The far outboard hand wing first must be accelerated by the drive to the previous downstroke speed. To all this be added an abruptly growing lift in the hand wing area. Correspondingly large is the impact load on the wing spar and the gearbox. Only then starts the full generation of the thrust.

The displacement of the lift on the hand wing takes place during the inner part moves downward and the outer part upwards. This rotating motion is aerodynamically unfavourable. But there are several ways to alleviate at least the problem of inertia of the bended hand wing:

a) Let the arm wing, like in birds wait at the top until also the hand wing is reached above.
For this purpose perhaps uncouple the wing from the drive or switch off the drive for a short time. One also can try it with a drive which under every power increase of the crank first always stretched a spring before the crank turns further.

b) On crank gears use drives with a speed controller
In the range of the dead centre of the crank with the reduced power consumption and there not yet loaded hand wing, they should not do react with an increase of rotation speed.

c) Making the mass of the hand wing small and concentrate it as close as possible to the wrist

d) Use a soft mechanical end stop in the wrist
Also elastic wing spars can help. This however causes undesirable stroke oscillations.

The bending should increase the thrust. But if the first part of the downstroke is done practically without thrust, the goal is not reached. Therefore the arm wing should take a break above.

6.3 Lift on hand wing

Which lift distribution on the bended hand wing is useful during the upstroke is unknown. As long as no tests and measurements in a wind tunnel are possible, one must approach by the method of trial and error to suitable angles of attack. Certainly, at least at the beginning of the bending, the different versions of lift distribution of Figure 7 can be used in the area of the hand wing furthermore. In the further bending then, however, the growing end-plate function of the hand wing remains disregarded.

On the basis of the following Figure 22 one can well imagine that the torque of the hand wing around the wrist with $c_\Gamma = 5$ is just sufficient in order to angle the hand wing down. But this lift distribution is achieved by the previous theory without phase shift of the lift displacement first in the middle of the upstroke. So, a bending only by aerodynamic forces would therefore start in this case not till the middle of the upstroke and end up directly there again. A lift distribution with about $c_\Gamma = 5$ so at least for a passive wing bending come into consideration only with the help of the phase shift. But also in doing so the support by aerodynamic forces is only very late.

To support the bending by aerodynamic forces as early as possible is required a greater displacement of lift towards mid-span. In the following Figure 22 is chosen as an example a lift distribution with $c_\Gamma = 2$. But also thereby only with the help of the phase shift is possible an early torque of the hand wing downward.

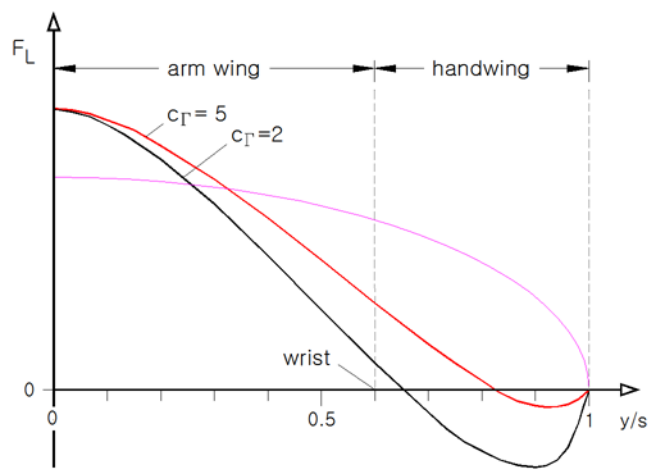


Figure 22. Lift distributions for a wing bending

With sufficient negative lift the hand wing turnout the flow coming from above with it bending downward. The lift thereby will be not as negative as in a stretched flapping wing. Nevertheless, it is advisable to limit the bending. The size of bending of the hand wing in birds depends on the thrust requirement or the respective beat frequency.

In ornithopters can achieve a similar soft limit of the bending when the axis of the wrist is inclined slightly inward at the rear (see Figure 23).

Thereby, the angle of attack of the hand wing increased during the bending and the resulting increase lift reduces this motion. If for example the hand wing is bended by 90 degrees downwards its angle of attack is increased by the angle λ. In this way, the hand wing comes to a standstill in an intermediate position. With the size of the additional angle λ therefore can influenced the size of the bending. It also accelerates the upward motion of the hand wing in the upper stroke end position. Approximately 10 degrees for the additional angle may be a useful starting basis for experiments.

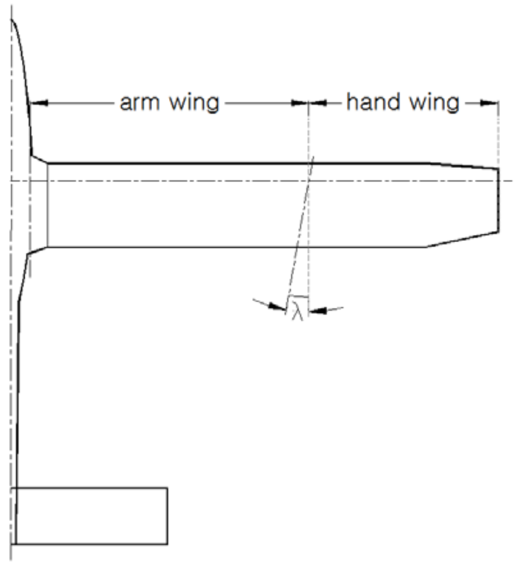


Figure 23. Additional angle λ of the wrist of an ornithopter in order to achieve an increase of the angle of attack in the hand wing during the wing bending.

A construction with very a large additional angle shows Figure 24. It replaces the wing twist in the forearm of the bird by a variable profile kink along the torsion axis (see also following Figure 25).

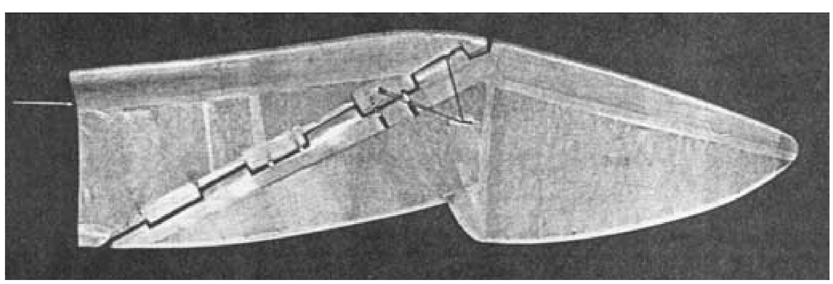


Figure 24. Flapping wing wigh additional camber of profile connected with an increase of the angle of attack particularly in the forearm on bending of the hand wing. A rubber thread supports the bending. Construction by Karl Herzog[9] 1963

During the upstroke, with maximum profile kink in bird is also present the maximum bending of the hand wing on the wrist. One can then well imagine that much lift is accumulated in this way at the outer end of the forearm. Subsequently, assists this lift by pressure compensation the upstroke of the adjacent hand wing and is thereby displaced in the direction of the wing tip.

Sometimes it looks, as if birds support the bending of the hand wing by muscle power, at least at the beginning of the motion. In ornithopters this can simulate by a spring which bends the hand wing towards the arm wing a little way downward. K. Herzog has executed such a thing with a rubber thread on one of his wing designs (see Figure 24). The strength of the spring you can select so that it just even can be full stretched by the lift in gliding flight. Possible effects on landing have to be considered. But a better method for bending shows Figure 20.

To design mechanically a strong wing bending for the cruise flight of ornithopters seems to be rather disadvantageous. But even with a small wing bending the appearance of slowly flapping ornithopters looks beautiful. Then it looks somewhat like the great role models.

7. Pivoting of the hand wing rearward

Besides the bending of the hand wing downwards one see in birds also a pivoting motion of the hand wing to the rear. In general, both bendings are applied simultaneously.

In birds twisting or even rotation of the hand wing is strongly restricted by the anatomy[11] of the wrist in the extended wing position (by wing skeleton, tendons, edge ligament for inclusion of the primary quills). Without downstroke motion then there is the course of the angle of attack of gliding along the whole wing. However, an elastic twisting of the hand wing, for example on downstroke is still possible and also a little additional twisting by muscle power. The restriction of the twisting will be stronger the further the hand wing tip is pulled forward by the thrust. Only by an at least small pivoting motion of the hand wing to the rear will be loosened this restriction. Its big advantage is the fast and powerless setting of the wing twist for the downstroke and the gliding flight. In addition, in birds together with the pivoting motion occurs simultaneously an area reduction and taper ratio by superimposed pushing of the primary feathers.

With the pivoting motion of the hand wing rearward the length of the arm wing is automatically shortened slightly (see Figure 25). This changes the wing airfoil at the elbow. Probably, the position of the maximum airfoil thickness, the chamber of airfoil and the angle of attack are changed. Also the sweep of the forearm displaces lift in the direction of the wing root. Under these circumstances, these changes can support, or in case of lower requirements even replace the displacement of lift by rotation of the wing root. Overall, by the change in shape of the wing the centre of lift will be shifted more towards the wing root. This is good for the concentration of lift in mid-span, but for ornithopters hardly to imitate.

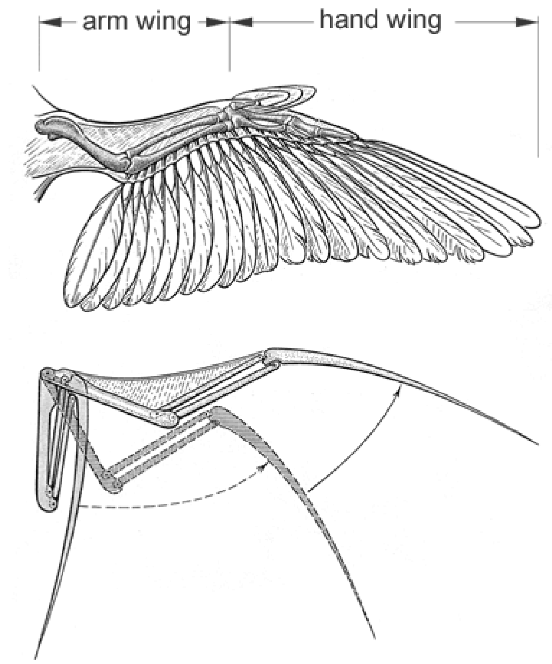


Figure 25.
Pivoting motion of the bird's wing, drawn by Karl Herzog

Also the wing as a whole performs a small pivoting motion. The drag on upstroke pushes it rearward. The thrust on downstroke, especially in the outer wing area, pulled it forward. The pivoting motions of the hand wing and this of the whole wing run synchronously and add up. So a trajectory like in Figure 26 feigned a too large bending of the hand wing, in particular forward.

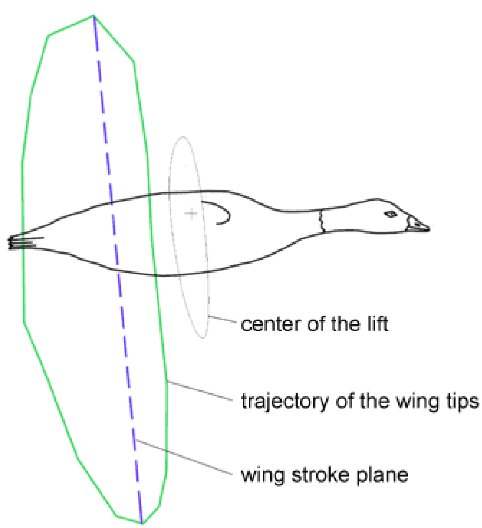


Figure 26.
Brent Goose in cruise flight with the trajectories of the wing tips and of the lift centre.
The lift centre was assumed here at 25% of the chord at the wing root.

With the pivoting motions of the wing also the centre of lift moves back and forth. Thus the bird is raised at the backside during the wing upstroke. At the end of upstroke then the bird's body and thus the wing roots are inclined slightly downward (see Figure 12). During downstroke with its wing pivoting and displacement of lift forward the bird's body is then erected again.

As long as one does not use the nodding of the fuselage on ornithopters, this restricts a little the benefits of the pivoting motion of the hand wing. But the involvement in the end plates effect remains. This applies probably especially if is executed a taper ratio at the end of the hand wing. As, however, affects a strong sweep or oblique inflow of the hand wing on it negative and positive lift is unknown.

8. Inclination of the wing stroke plane

The wing stroke plane is an imaginary plane which is sweep over by the wing axes during the flapping motion. An inclination of the wing stroke plane can be achieved in two ways. Either the inclination of the flapping axis to the axis of the fuselage is fixed installed or one turns the fuselage axis in relation to the direction of flight when flying. In the latter case, the inclination of the wing stroke plane is quasi created by flying.

The difference between the two methods lies in the behaviour of the angle of incidence along the whole wing. If the inclination of the stroke plane is created by flying it changed, but not with the installed inclination. In the following only the installed inclination of the wing stroke plane is considered and short labelled as "inclination".

In cruise flight of birds not always can be seen the inclination. If so, it then runs mostly from rear-top to front-bottom. As shown below, this has advantages for the generation of thrust. But the wings are moved not only in the stroke plane. Especially at the outside they are also pulled forward by the thrust on downstroke and pressed back by the wing drag on upstroke. The result is an approximately elliptical trajectory of the wing tip, whereby the longitudinal axis of the ellipse lies in the stroke plane (see Figure 27).

The inclination operates with the lift on upstroke on the nodding motion not always in the same direction. It supports in birds the nodding always only towards the end of the stroke motion. At the beginning it worked against it. With big negative lift in the hand wing area it may also be reversed. Without detailed knowledge of the various influences factors cannot be described here the effect of the inclination to the nodding motion.

Unequal effects of both stroke cycles on the nodding motion can be compensated by shifting of the middle lift centre in relation to the centre of gravity. This can best be achieved by the average sweep of the wings. The adjustment of the thrust force as a result of the inclination in front slightly upwards in cruise flight is probably of secondary importance.

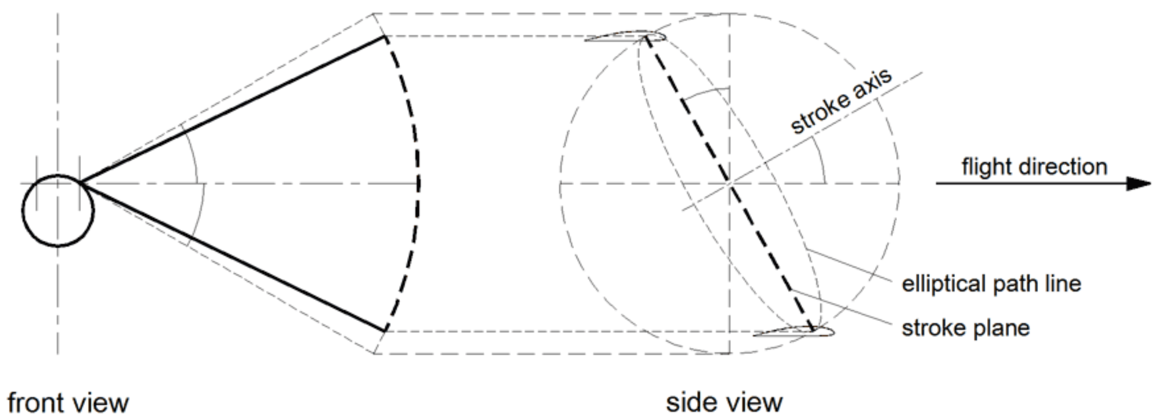


Figure 27. Installed inclination of the wing stroke plane by tilting the stroke axis in relation to the fuselage axis.

A great advantage of the inclination is the increase of the approach velocity on downstroke in the outboard wing area. The small forward motion of the wing tips is added to the flight velocity. Because the lift increases quadratically with the speed, the inclination is absolutely significant. It helps on downstroke to increase the lift and thus also the thrust force in the outboard wing area. A particular advantage of this is that thereto must not be extended the working area of the lift coefficient of the airfoil. During upstroke the smaller approach velocity in the outboard wing area supports the downsizing of the lift.

The inclination therefore helps in the lift shifting along the span and thus in thrust generation. With increasing inclination, however, decreases more and more the up and down motion of the wing (see Figure 27). This comes at the expense of the thrust generation. As shown in the calculation of a large ornithopter model, a weakly pronounced climb flight optimum is at an inclination of about 10 degree. But at the same time there is a minimum for the distance of flight (see handbook “Wie Ornithopter fliegen”, chapter 8.8[2]).

9. Energy storage with springs

A first reference on saving the upstroke energy in case of technical aircraft comes by Otto Lilienthal[5]. In his suggestions for the construction of flying apparatus he wrote among other things (in German):

“30th.— It would be of advantage to store the effect of air pressure during the upstroke so that it may be utilized again during the down-beat, and thus save work.”

Thus, when a spring is arranged so that is tensioned by the wing on upstroke and it remove the tension with the downstroke it fulfils this requirement (see following Figure 28). The cycle of wind turbine energy then can be described as follows.

On wing upstroke in the wind turbine mode, thereby occurring additional drag reduces the airspeed of the flight model. Thus detracts the kinetic energy of the model mass. Via the upstroke motion of the wing the relevant amount of energy is stored as tension energy in the spring. During the downstroke the spring tension is removed and gives the energy back again to the wing. There it is converted into thrust. The thrust accelerates the model and gives back the kinetic energy to the model mass. The energy related to the additional drag during upstroke therefore is not lost. It can be recovered with the aid of elastic elements.

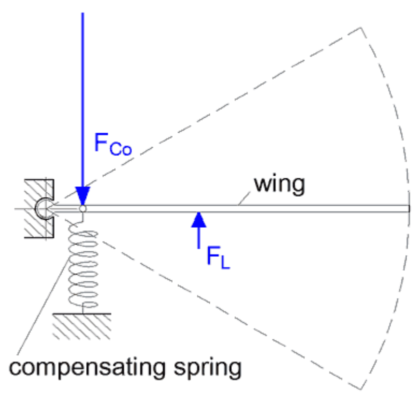


Figure 28. Arrangement of a pull spring as lift compensation spring
F_{Co} = force of the compensation spring
F_L = lift in gliding flight

This energy cycle of course is lossy. However, the losses of the wing upstroke are also existent if the wing worked in the propeller mode. The induced drag by the calculation program in the propeller mode is even throughout greater than in the wind turbine mode. The advantage of the whole story with the wind turbine mode is the significant lift that can be generated also on upstroke.

Because the centre of lift of the wind turbine force lies always near the wing root, the thereby converted energy in the spring is generally not very large. The spring can therefore be relatively small. It just needs to balance with its average force the average torque of the in wind turbine mode operating wing. The spring is then able to absorb all generated energy of the wing during the upstroke. The problems thereby are the unequal forces of wing and spring during the upstroke motion. The drive therefore must take over the force balance and the controlling of the upstroke velocity throughout the whole upstroke. But on average it should idle during the upstroke. With a real speed governor this may be possible.

If one indeed already used such a spring, it can also be used very advantageous for the storage of drive energy. To achieve that, the spring must be of larger dimensions. If it is then tensioned not only by the wind turbine function of the wing but also by the drive during the upstroke, it also stores that energy. The spring supports the drive on the down-stroke and releases thereby the stored energy again.

Thus the drive will be more loaded on the upstroke and less loaded on the downstroke. Because the lift forces on the wing or more precisely their torques acts just inverse, the peak load is reduced on the downstroke. In this way the drive system is operating more equally and with a considerably smaller peak load during a flapping period. Thus, motor and gear can be dimensioned significantly lighter. With a wing upstroke in wind turbine mode thus can approximately halved the peak load of the drive for flapping flight.

The spring will be advantageously dimensioned in a way that it just balanced with its force the torque of the average lift during a flapping period in the middle position of the wing. This average lift during a flapping period equates about to the lift in gliding flight. Furthermore, the spring force should be relatively evenly during the whole flapping period. Therefore the spring rate should be chosen as small as possible. However, a steel spring is then relatively strong, large and heavy. A gas spring despite of worse efficiencies may be here perhaps better.

The spring compensates the lift which exists in average on the flapping wing. To distinguish it from other springs in a flapping wing drive I call it lift-compensation spring, or just as “compensation spring”.

The compensation spring also facilitates the fixing of the wing in glide position during the flight. However, when starting and while decreasing the lift force during landing it pushes the wing tips down. If for holding of the stretched wing position the cogging torque of the standing motor is not sufficient as a brake, so there is necessary an additional brake or lock mechanism.

A third possibility to use the wind turbine energy is the acceleration of the wing mass. In each wing beat between of the two end positions first the wing mass must be slowed down and then accelerated again in the opposite direction. In the technique in such cases are used springs. One obtained so an oscillating system that keeps moving in the theoretical ideal case (without damping by the wing area) without external supply of energy. The drive is then no longer loaded by acceleration forces. In order to blend out theoretically easier the influence of gravitation in a corresponding experimental arrangement, the swinging wing is shown vertically suspended in the following Figure 29.

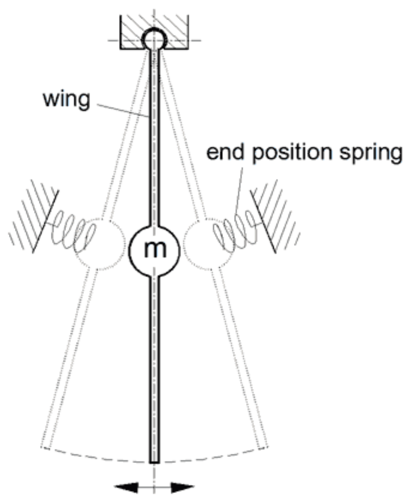


Figure 29.
Swinging wing mass “m”
between two end position springs

On the flapping wing acceleration forces are superimposed by the lift forces. In the lower end position, the lift supports the deceleration and acceleration of the wing mass. In the upper end position, it works in opposite to the motion reversal.

In practice, you should take the following way. The spring of the lower end position will be simply omitted (see following Figure 30). The deceleration of the wing mass at the end of the downstroke can be taken by its lift. Subsequent the wind turbine function of upstroke drives the wing mass in the opposite direction. The closer configuration of this process and the advantage for the lift are described in chapter 5.5.

The upper end position spring is initially sized for their task to accelerate the wing mass. For this purpose, the inertial force with its radius of gyration is proportionally converted to the spring force and its lever arm on the wing. If no separate compensation spring is used, so the end position spring in the compressed state will be additionally strengthened dimensioned by the force which is necessary to balance the lift on the wing in gliding flight. The lift in the short-term standstill of the wing during the motion reversal corresponds theoretically about to that of gliding flight. So the end position spring can perform the acceleration of the wing mass and simultaneously act towards the interfering lift force.

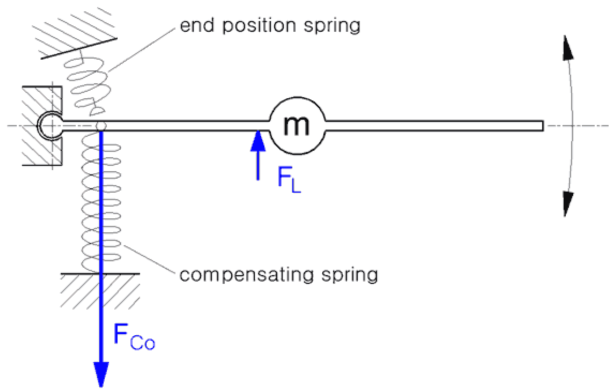


Figure 30. Arrangement of compensation spring and end position spring on a flapping wing
The compensation spring here is designed as a pull spring and the end position spring as a pressure spring.
F_{Co} = force of the compensation spring
F_L = lift in gliding flight

The kinetic energy that flows during upstroke by the wind turbine effect in the wing mass will be absorbed during decelerating by the local end position spring in the upper end position. The spring gifs off again subsequent its tension energy into the acceleration of the wing mass in downstroke direction. In this way it supports the drive on downstroke and also with the thereby generated thrust the acceleration of the model mass. The end position spring acts nearly like a shortened compensation spring. With a suitable spring characteristic both spring functions also maybe combined in only one spring. The use of an end position spring is worth especially with large wing weight.

The benefit of wind turbine energy during the upstroke can be made both by direct generation of thrust in the outer wing area and with the help of compensation springs or end position springs. All three methods also can be combined. Indeed the mentioned springs increase the model weight, complicate the construction and make difficult the handling, for example, during a test run. Hence one should also look for other solutions.

In birds, some kind of springing could facilitate the idea, how it is possible for them to glide for hours with outstretched wings without much muscle power. But so far for me there is unfortunately nothing known about such things.

10. Usage of a speed governor

In propeller driven model aircrafts the drive controller works mostly as a normal speed controller. With it you can vary the rotation speed however the setting speed varies also with changing of the load. In contrast, real speed governors maintain the set speed constant even under changing loads.

A really rpm-controlled flapping wing drive provides several advantages. In the normal case the drive is virtually very unevenly loaded during a flapping period. Only the wing downstroke requires the full drive power. In the case of non-controlled drives therefore the speed increases significantly during upstroke. Moreover, the most commonly used cranks in the mechanism, in the top and bottom dead centre does nearly require a drive torque. There the motor runs practically at idle. It responded with a significant increase of speed of rotation. Additionally are coming torque oscillations which results from elastic wing spars. The moment of inertia of the motor smoothed the speed curve slightly (With an outrunner motor or with a flywheel you can increase this effect and even use it for the storage of wind turbine energy.). But one certainly cannot speak of a continuous or even sinusoidal motion process during a beat period when using unregulated drives. On flying ornithopters you can even hear the non-uniform drive operation.

If the lift on upstroke is large enough, also with a running motor the wing can be the propulsive part. It then tries permanently to accelerate the motor. This now works as a generator. From the preset target speed the brake of the controller becomes active and keeps the speed constant. The thereby imparted wind turbine energy can be used depending on the controller type to convert it into heat or to conduct it with an energy recovery system into the battery. In the latter case the excessive upstroke energy will be buffered in the traction battery. It then can be used again on downstroke.

However, the energy balance of regenerative brake deteriorates considerably by the effectiveness of the mechanism, motor, electronics and battery on the round trip of the energy (overall efficiency lower than 50 %). In addition, the most widely used cranks impaired this method by their motion characteristic. Motor and gear are also not relieved during downstroke. The gear even must be strengthened, because it must withstand the changing load directions. Nevertheless, a regenerative brake can in principle take over the storage function of a compensation spring.

When it is possible to keep the excess wind turbine energy small, also a real speed controller is useable with a brake that converts the energy into heat, at least at the beginning the development. The controller, however, is to protect against overheating.

11. Requirements for the ornithopter construction

A requirement for a significant lift generation during upstroke is a suitable wing design. Whether the wing can work in wind turbine mode depends crucially on the upstroke velocity and the thereby existing distribution of the angle of incidence along the span. The wing must be able to keep positive angles of attack in spite of existing lift.

This requirement on torsion elastic wings is not so easy to fulfil. But you can control the wing twisting, by the drive mechanism[E] or by servos[F]. Also, it can be used the displacement of lift[G] along the half span. Each of these methods has advantages and disadvantages. With all these processes on ornithopters are usually influenced only the twisting of the arm wing.

Normally be still added, intentionally or unintentionally an aeroelastic twisting component. It is determined by the size and location of the lift force, the elasticity of the used components and the location of torsion axis of the wing. If the torsion axis lies very far forward an increasing lift, for example on downstroke, strengthened the torsional moment. At the same time the pressure point of the lift force moves forward and so reduces the torsional moment. So the size of the lift force and the position of its pressure point behave contrary. Therefore it is difficult to project the size of the aeroelastic wing twisting. It only works

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[E] Already E. v. Holst (1940) has effectuated with his rubber powered crank drive of his flapping wing models not only the flapping motion but also the wing twisting (please see http://www.ornithopter.de/english/herzog.htm#crank). Also the wing twisting of the ornithopters Truefly (please see http://truefly.chez.com/) and EV1 to EV5 (please see http://www.ornithopter.de/english/picture1.htm) has been controlled by their drives.

[F] On the reproduction of the Quetzalcoatlus Northropi (please see http://.www.ornithopter.de/english/wings.htm#maccready) by Paul MacCready and on the SmartBird (please see https://www.festo.com/group/de/cms/10238.htm) servos were used for the continuous adaptation of the wing twisting. On SmartBird only the twisting of the long hand wings was active controlled by servos.

[G] The displacement of lift along the half span has controlled the twisting of the ornithopters EV6 to EV8. This applies especially to the thereby developed aeroelastic controlled articulated flapping wing (please see http://www.ornithopter.de/english/articulated.htm). Thereby the shifting of the pressure point along the chord plays only a subordinated role.

reliably if the torsion axis is positioned far ahead. In addition it is not so easy to achieve a precisely defined twisting distribution because the mechanical properties of the wing structure against torsion mostly are missing.

But the aeroelastic twisting has the advantage that it can adapt flexibly to different flight situations also without a sensor-system. In the most known flapping wing designs hand wings are exclusively twisted aeroelastically. Thereby, however, absolutely lift can be generated even on upstroke. It just has to be present even in unloaded condition a positive angle of attack.

To minimize the required thrust, first of all you must try to make the parasite drag of the ornithopter as small as possible. In the field of fuselage and tail an aerodynamic design is still relatively easy to implement. But in the case of the wing this means almost inevitably the transition from a membrane to an airfoil with a good lift-to-drag ratio. For a high effectiveness of the flapping flight good airfoils are even indispensable. They improve also the often practiced gliding flight of the ornithopters, but restricted in flapping flight the possibilities in the outer wing area.

In the usual airfoils the lift coefficient has only a relatively small operating range. Unlike membrane wings they are able only in a very limited extent to work with strong negative lift coefficients. In general, airfoils works only well with positive lift coefficients.

However, thick airfoils are able to manage passable with positive and negative lift coefficients. But they have a relatively high drag. Nevertheless, one should not ignore them completely. Furthermore, in the outer wing area with the airfoil selection is to ensure, that in addition to the projected operating range of the lift coefficient also reserves are available. In practice the flight situations often differs to the intended. Thus it is advisable to work only with lift distributions whose negative part is small. This is the case only with circulation characteristic numbers c_{Γ} with values larger than 4 (see Figure 7). This further more limits the thrust generation.

To solve the problem with the too small operating range of the lift coefficient or the strong alternating approaching flow directions one has already experimented with artificial primary feathers at the wing tip[H]. They can react more flexibly with their angle of inci-

[H] For example in my ornithopter model EV7b, please see http://www.ornithopter.de/english/picture3.htm#ev7b dence to changing approaching flow directions than a continuous surface. For the application of slats (e.g. Alula), flaps and other lift aids regrettably are still missing suitable flapping wing constructions.

Altogether, you can also look critical the changeover to more lift generation. Instead of the lift problem there is a thrust problem. Rises off ground or steep climb flights are only possible by changing the mode of operation of the flapping wing. In addition, the technical requirements are relatively high. They can be summarized as follows:

1. It is very advisable to use airfoils with a good lift-to-drag ratio. Especially in the outer wing area they should have a wide operating range of the lift coefficient and if possible they also should be able to work with negative angles of attack. A large wing depth along the whole wing span helps to increase the reserves of the lift coefficient. But they are combined with a higher airfoil drag.

2. There is required a wing design which can maintain a positive angle of attack also at existing lift during the upstroke.

3. The displacement of lift along the half span is done in particular by a suitable wing twisting. But with this alone achievable concentration of lift in the mid-span suffices only for moderate thrust and moderate lift on upstroke. An inclination of the wing stroke plane supports the displacement in both stroke cycles.

4. On upstroke, for the concentration of lift in mid-span or for boosting thrust comes into consideration a rotation of the wing root (only on upstroke). In addition can be provided a bending of the hand wing downward. With strong concentration of lift then also high lift no longer interfered with the thrust generation. Thereby helps a great wing depth and a strong airfoil camber near the wing root.

5. On upstroke, the wing shall only be powered by aerodynamic forces. In normal case, even is required a force against the upstroke motion. Preferably this is done by negative lift with generation of thrust in the outer wing area.

6. On upstroke, with insufficient lift concentration in mid-span the excess wind turbine energy is to pass into a device with energy saving (e.g. springs, battery, flywheel) which then supports the downstroke.

7. For the downstroke, also outside of the wing the chord should be large particularly where in birds is effective the Alula.

8. To increase the thrust, the angular velocity can be maintained approximately constant during long distances on downstroke.
9. The parasitic drag of the whole aircraft must be minimized.

If one like to imitate the excellent flight performances of birds or simply want to fly very energy-efficient, one has probably give more attention to the generating of lift during the upstroke.

Information about the program "Orni 1"

All lift distributions are shown here was calculated with the computer program "Orni 1"[4]. It applies only to the simplest way of flying, thus the unaccelerated level flight and the gently inclined climb flight. Furthermore it is restricted to straight upswept wings under quasi-stationary flow conditions. These frame conditions are generally applied here.

The calculation program has the great advantage that the used lift distributions have a relatively small induced drag. This is also advantageous for birds. So they probably work in the cruise flight with similar lift distributions.

With the calculation program "Orni 1" you can view all corresponding distributions of lift coefficient, downwash, angle of incidence and angle of attack for a rectangular wing. However, some terms there are otherwise defined (lift = transverse force, vertical force = lift, thrust or additional drag = propulsion).

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