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Translated from the orginal series of articles by Karl Herzog
in MECHANIKUS magazine (Germany 1963-64)

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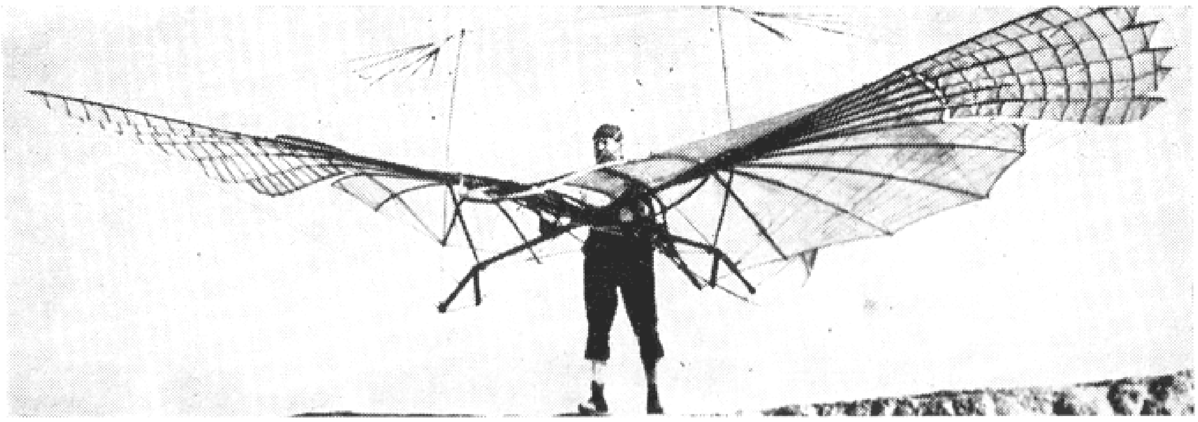

FLAPPING WING FLIGHT IN NATURE AND SCIENCE

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Experiments in the history of Aviation

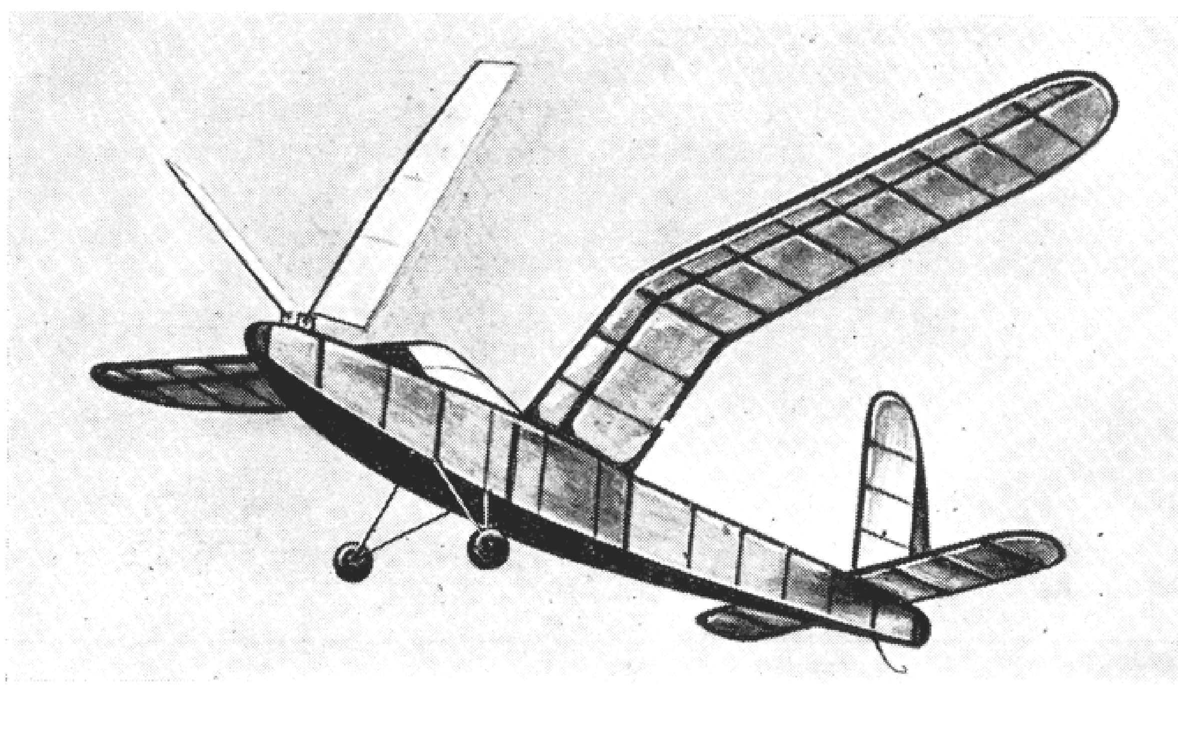
ALL the research and development in aviation throughout the ages has brought us to the stage where in nearly every field success has crowned man's efforts.

Gliders, sailplanes and powered aircraft are all at a stage where only refinements to increase performance and safety are possible.

All the fundamental laws are known and understood. Only in one area has man failed to obtain success and this is to emulate the flapping wing flight of the bird.

Otto Lilienthal built a flapping wing with a span of 8 metres and a weight of 40 kg. (Fig. 1). Lilienthal made several gliding flights but died before he could make flapping wing flights.

Alexander Lippisch in the years before World War II built many flapping wing models (Fig. 2). In some the propeller was replaced by two small wings, which on the upswing were turned negative and positive on the down swing.



The span of one was 3 metres, the weight 1950 grammes. A 4 c.c. Kratmo engine in the fuselage nose drove the small wings at 280 beats per minute. With R.O.G. heights of 4 to 5 metres and durations of 4 minutes were attained. A hand launch from a slight rise resulted in a record flight of 16 minutes 8 seconds with a height of 45 to 50 metres.

Of special interest is Schwan I by Dipl.-Ing. Walter Filter (Fig. 3). It featured a very short fuselage with the wings in the mid wing positions. The wing was in two distinct halves, a very massive inner wing and a strong flapping part with a flapping angle of 75°. Each flapping wing part was divided into six long and narrow flaps. These flaps did not overlap but were next to each other and capable of rotating round their longitudinal axis, so that on the down beat the T.E. was raised somewhat and on the up beat somewhat downwards. The aircraft was powered with a 4 h.p. motor, which was in fact found to be not powerful enough.

Recently experiments were also conducted in the U.S.A. and England.

An outstanding example amongst these is the Ikarus designed by Emiel Hartman. Ikarus was built for him in 1959 and tested at the end of that year and in the spring of 1960 (Fig. 4). On test the height obtained was only 3 metres, but nevertheless constituted a significant stride forward on the road to man-powered flight.

Both wings were hinged at the fuselage in the C.G. position. A scissor type lever activated by a rubber bungee and springs held the wings in the up position against their own weight. (Fig. 5).

The wings were pulled in the down position by five strong cords, fastened to the centre of the span. (Fig. 6).

During the up and down beat the finger type wings are turned in such a way that the part of the wing behind the main span gets more washout.

The flapping wing action is driven by muscle power.

The launch was aided by a powerful bungee cord..

On tests heights of 3 to 3·5 metres were obtained under power after which the aircraft glided to earth. Most tests were made with Auto-tow.

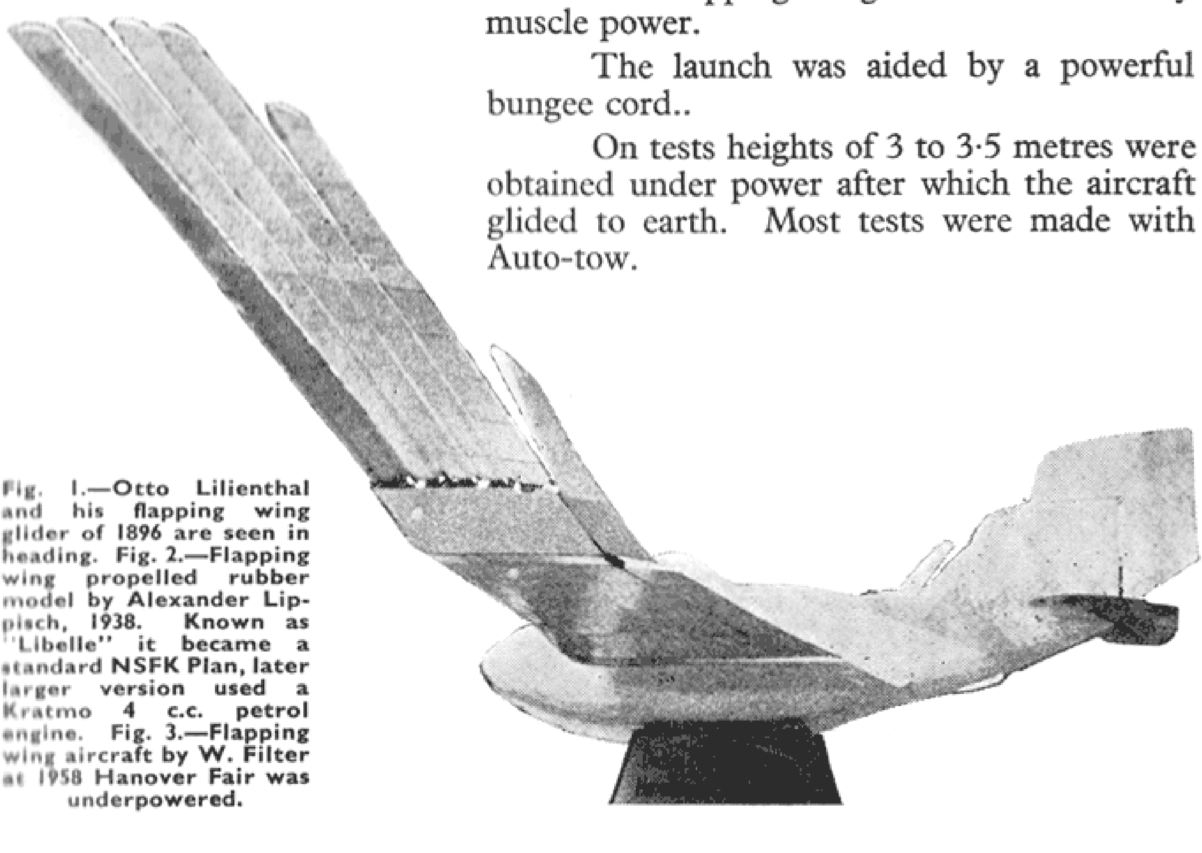


Fig. 1.—Otto Lilienthal and his flapping wing glider of 1896 are seen in heading. Fig. 2.—Flapping wing propelled rubber model by Alexander Lippisch, 1938. Known as "Libelle" it became a standard NSFK Plan, later larger version used a Kratmo 4 c.c. petrol engine. Fig. 3.—Flapping wing aircraft by W. Filter at 1958 Hanover Fair was underpowered.

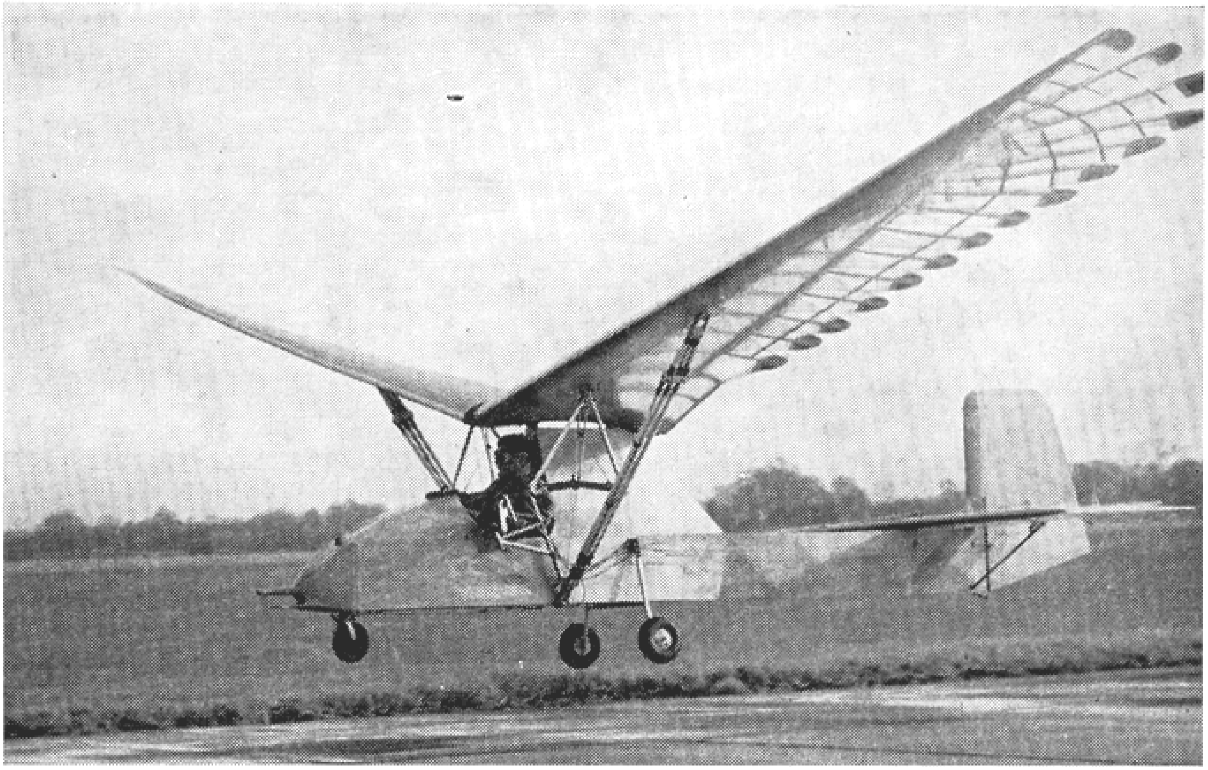
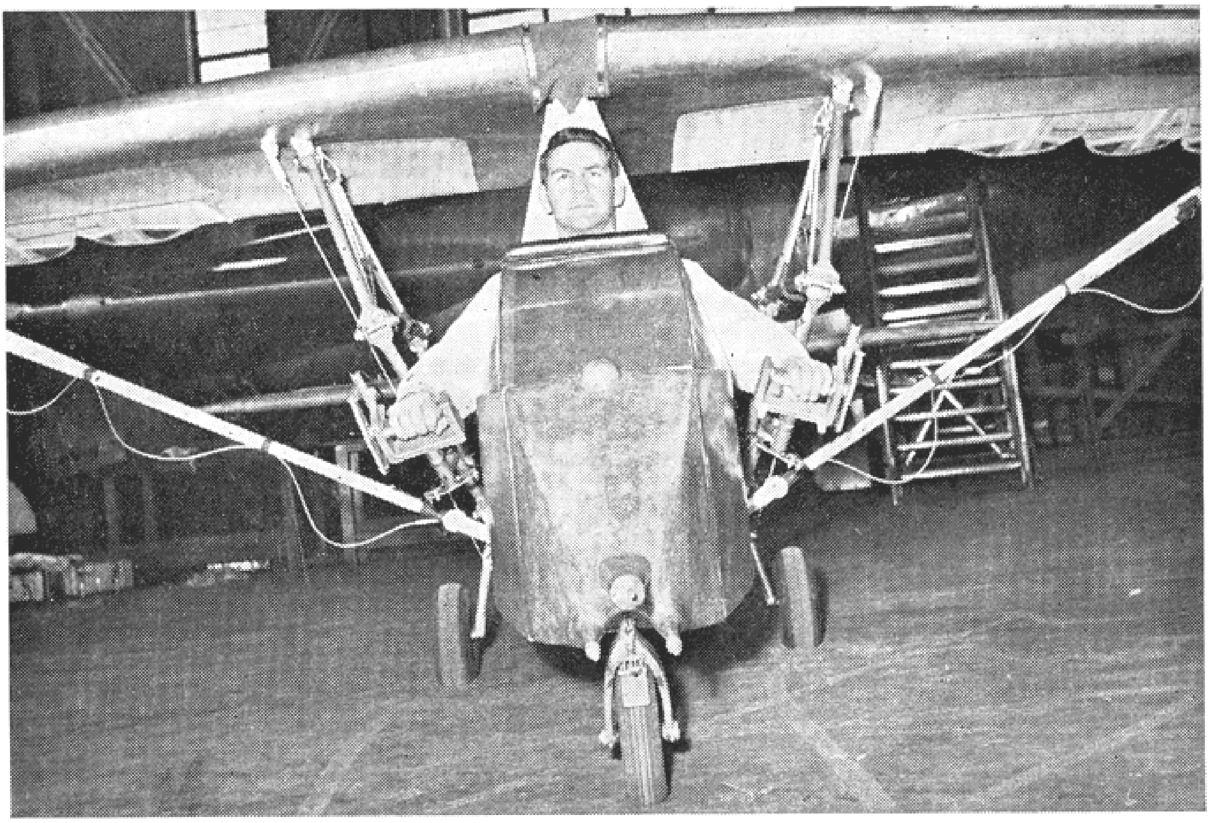


Fig. 4 above shows Emiel Hartman's "Ikarus" gliding after an auto-tow at Cranfield in 1959. Fig. 5 below illustrates the mode of power by rowing action and Fig. 6 opposite shows wings in the depressed position (*Daily Mail* photographs).

Biophysics of Birdflight

A bird is able to lift himself into the air by flapping his wings. For this he uses very powerful breast muscles, which account for approximately $\frac{1}{8}$ of the



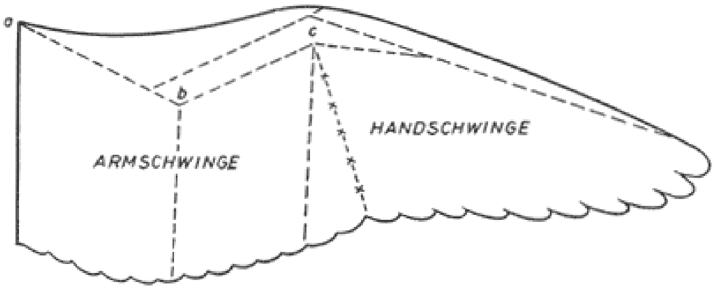
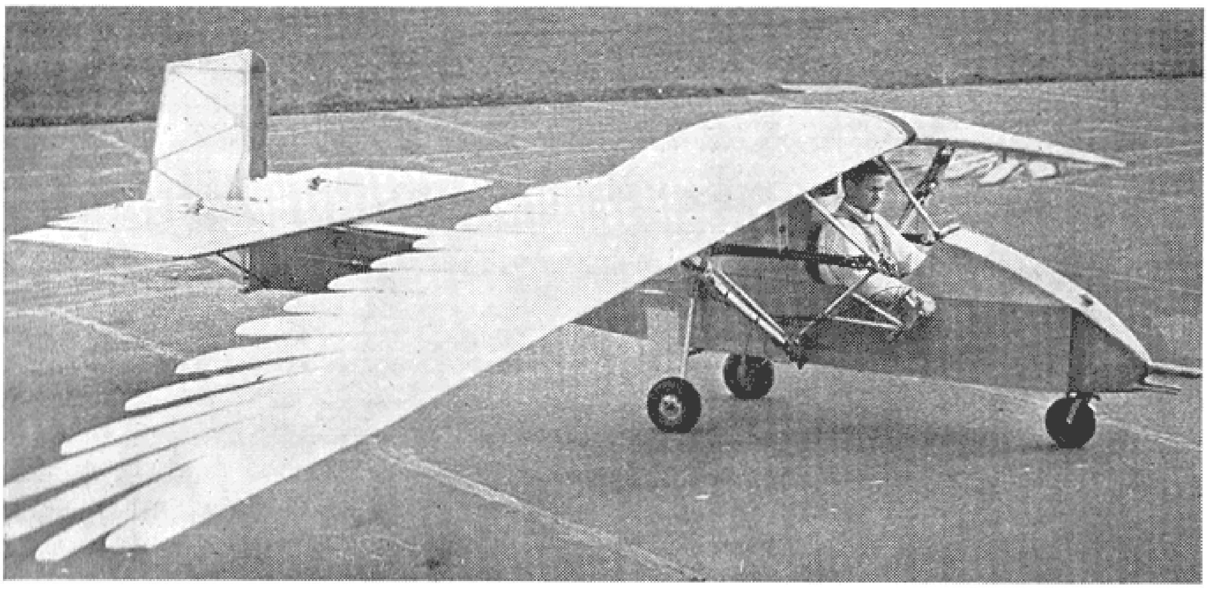


Fig. 7.—The "arm" and "hand" areas of a flapping wing.

total weight in smaller birds. One would think that the body of the bird would rise, when the wings flap down, and fall, when the wings go up. As is well known this doesn't happen, the body follows a straight path with approximately constant velocity.

To help us understand the bird wing, which incidentally is not much different from the human arm, it will help if we make a wing out of stiff paper. The planform is shown in Fig. 7 and can be transferred to stiff paper complete with the fold lines. After cutting to shape fold the wing along the dotted lines



downwards. This causes the areas alongside to move back. Dotted lines with crosses mean that the neighbouring areas are folded forward.

The small triangular area alongside the dotted line with crosses divides the wing now in two parts, *i.e.* the arm and the hand.

Point A is the shoulder joint, point B the elbow and point C the wrist. The elbow joint *b* is somewhat higher than *a* and *c*. If one now imagines that our paper wing is covered with feathers the hard edges are no longer in evidence.

The wing is now convex on the upper surface and concave on the bottom with the max. camber well forward.

This camber flattens out quickly not only behind the point of max. camber, *i.e.* chordwise but also spanwise. A bird wing could be compared with a cambered plate fitted to a trapezoidal wing with the camber decreasing towards the tip.

The division between the arm and hand part of the wing is important.

As the hand part can turn in the wrist joint it can adopt a different angle of incidence than the armpart.

As soon as the drag sets on the trailing edge of the hand it will deflect

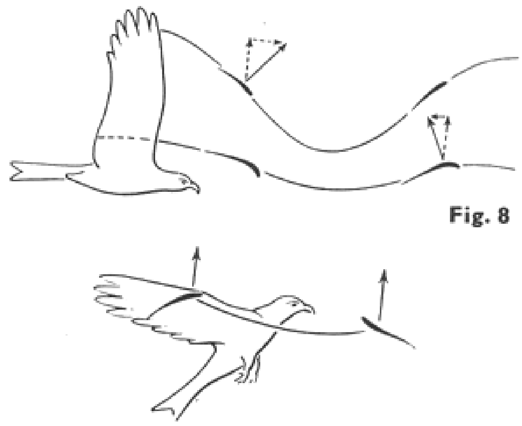


Fig. 8

downwards on the wing's upswing and upwards on the wing's downswing.

This action is held between definite limits by powerful muscles, and consequently can be controlled at will.

Hence a weak or strong flapping motion or gliding flight can be obtained. The bird uses different parts of his wings to support his weight during the upswing and downswing.

During the downswing he supports his weight with the parts of his wings closest to his body and on the upswing with his outer wings (Fig. 8). The inner wing halves are nearly always aimed in the direction of flight, while the outer ones rotate.

The arm furnishes the necessary lift to support the bird, while the hand acts as a propeller. For the R.O.G. the bird can rotate his wings such that the wings move backwards and forwards instead of up and down. The propelling force horizontally now becomes a vertical one and the bird takes off. A comparison between bird wing section and say Clark Y, shows that a bird wing is highly cambered with the max. camber well forward. To obtain the same lift for minimum drag a Clark Y airfoil will need an angle of attack of $-26°$ against a bird wing's angle of $-10°$. On the upbeat the figures are $+40°$ and $+17°$ respectively.

Erich Jedelsky of Vienna has for many years experimented with highly cambered airfoils. The best results were obtained with airfoils in which, over the last $\frac{1}{3}$ of the chord the lower surface came so near to the upper surface that there was only a paper thickness left.

On these highly cambered airfoils there is a considerable centre of Pressure travel making the wing sensitive to gusts, which for gliding flight is a definite disadvantage. In gliding flight the bird is subject to the same laws as the model. The C.G. is below the centre of lift and as the bird glides in the shoulder wing configuration the C.G. is well below the life centre and it has ample pendulum stability. During flapping flight however the wings are sometimes above, alongside or below the body. The body is therefore sometimes in a stable, sometimes in an indifferent and sometimes in an unstable state.

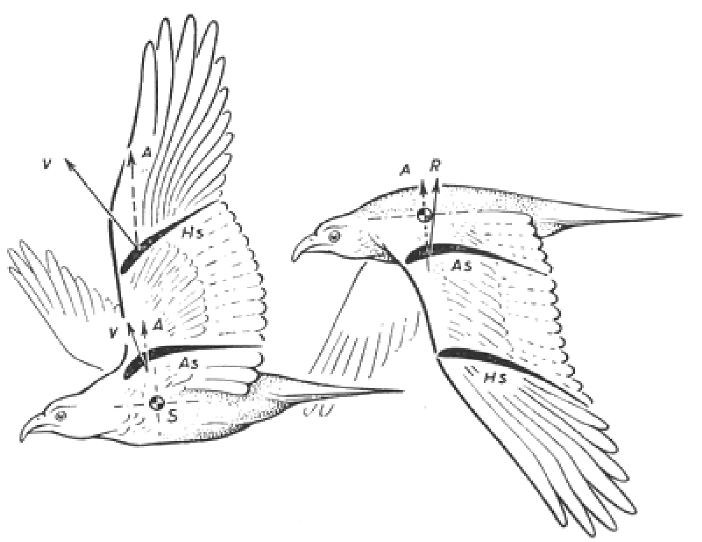


Fig. 9.—Force distribution on a bird wing during flapping wing flight. On the wing down beat (left figure) the weight of the bird is mainly supported by the outer wings (Hs). The forces show a forward component (A = lift, V = Forward Force). On the wing up beat (right figure) the outer wing is turned upwards. The weight is now supported by the inner wings (As). The lift component is directed somewhat backwards. During the wing motion the lifting force remains the same, the forward force is always larger. S = Centre of Gravity.

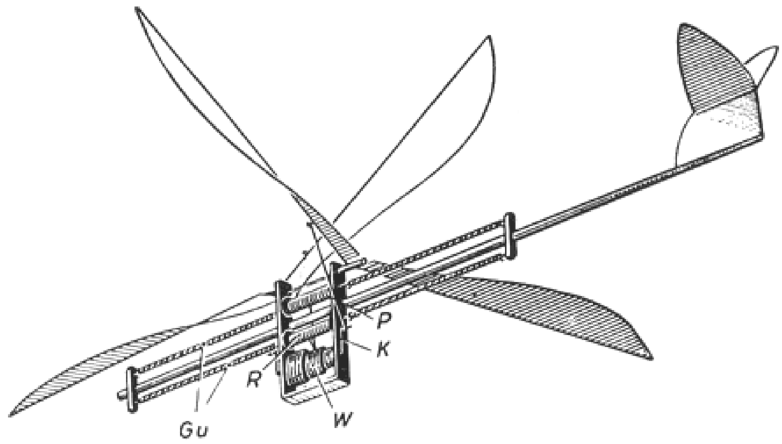


Fig. 10.—Dragonfly and its mode of power. Gu = rubber motor. R = thread roll. W = stepped roll plate. K = Crank. P = connecting rod. This is the Eric V. Holst design.

One would think that the bird has to do something about this, in fact it doesn't have to as is shown in Fig. 9. During the downbeat the weight is carried mainly on the somewhat swept forward outer wings (hands).

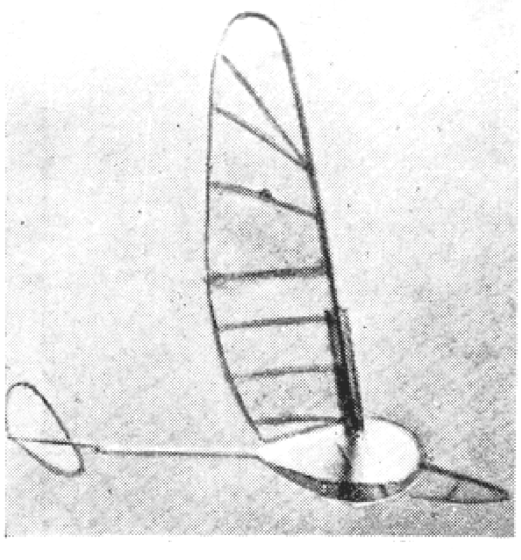
However their Centre of Lift is now somewhat ahead of the C. of G. and the bird is somewhat tail heavy. The wing couple works however against this. On the upswing the weight is carried by the inner wing halves and the wing is brought upwards in such a manner that C. of L. and C.G. are in line.

Ornithopters of E. v. Holst

Dr. Erich von Holst studied for many years the flight of insects and swallows. In 1939 he built a model insect to prove his observations. The model had a span of 35 cm. and the low weight of 7 grams. The model was constructed from straws, sewing silk and tissue paper.

In spite of the small rubber motor a height of 2 metres and a duration of 44 seconds was obtained.

In 1940 von Holst built a Dragonfly (Fig. 10). The model had a span of 53 cm., a length of 48 cm. and an A.U.W. of 12 grams. As the dragonfly the model had two pairs of wings, which are turned during the flapping motion. Both wings which have dihedral are on a common axis. Motive power is supplied by a rubber motor which drives the wings via a system of rollers and threads. Through the thread system the one wing goes up while the wing behind goes down. On the other side the action is reversed.



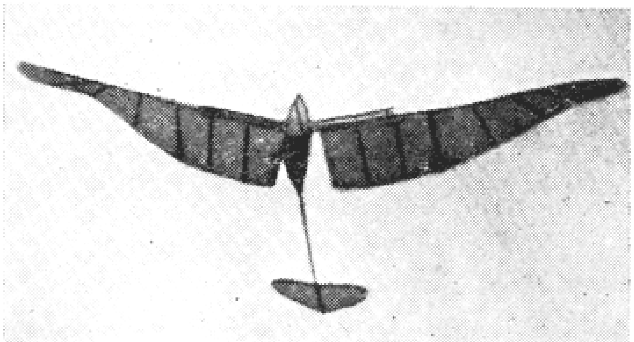


Fig. 11.—The "Buzzard" in a climb and Fig. 12 above, in horizontal flight, see Figs. 13, 14 for more detail.

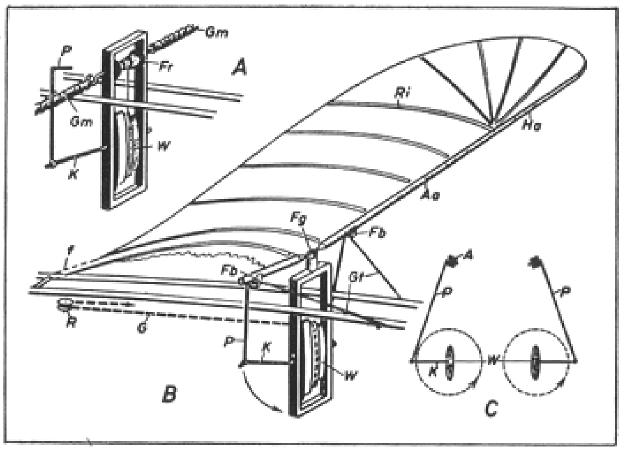


Fig. 13.—Driving mechanism with rubber motor as developed by Prof. E. v. Holst.

E. von Holst's Buzzard (Fig. 11) had an overall length of 45 cm., a span of 97 cm. and a weight of 24 grams. Two strong rubber motors, one in front of the wings and one behind the wings powered the model. The slinking angle is approximately 45° (Fig. 12).

The most interesting part of E. von Holst's models is the drive mechanism (Fig. 13). The heart of the mechanism (Fig. 13A) is a thread drive, which consists of a stepped or conical formed reel (Fr) and a stepped eccentric rollplate (W). Because of the eccentricity the downbeat takes place with a larger force than the upbeat. When turning the rollplate (W) by hand the thread is unrolled from the reel (Fr) and onto the plate (W) and at the same time the rubber motor (Gm) is wound up. As soon as the rollplate (W) is released the reel (Fr) is turned by the rubber motor and the thread winds back. The rollplate (W) drives the cranks (K) which in turn drive the connecting rods (P) to the wing halves.

Later von Holst simplified the mechanism, as used on the Swan (Fig. 13B). Here a long rubber strand was led over several rollers (R) in the fuselage. The stretched (not wound) rubber band was taken round the various diameter steps of the rollplate (W). When only slightly stretched the band was brought round the larger diameter and as the tension increased round the smaller diameter. In Fig. 13B the direction of rotation of the cranks (K) is shown.

Fig. 13C shows the section of the connecting rods on the fixing point (A) where small brackets (F6) make the connections. The rubber strands G_t fixed to F_b on the one hand and to hooks on the fuselage on the other half to make the downbeat stronger than the upbeat, as they are stretched both forward and outwards. Only one rib (Ri) is fixed to the L.E., all other ribs are only fixed to the L.E. through the covering. The T.E. of the innermost rib is fixed to the fuselage. Hence the inner wing part is not completely free to follow the action of the L.E. Once flapping, the outer part of the L.E. transmits its action via rib (Ri) onto the outer wing, while the inner wing is kept back. Hence a twist is developed across the span.

Throughout the construction emphasis should be laid upon precision.

Building Instructions for the Buzzard (Fig. 14)

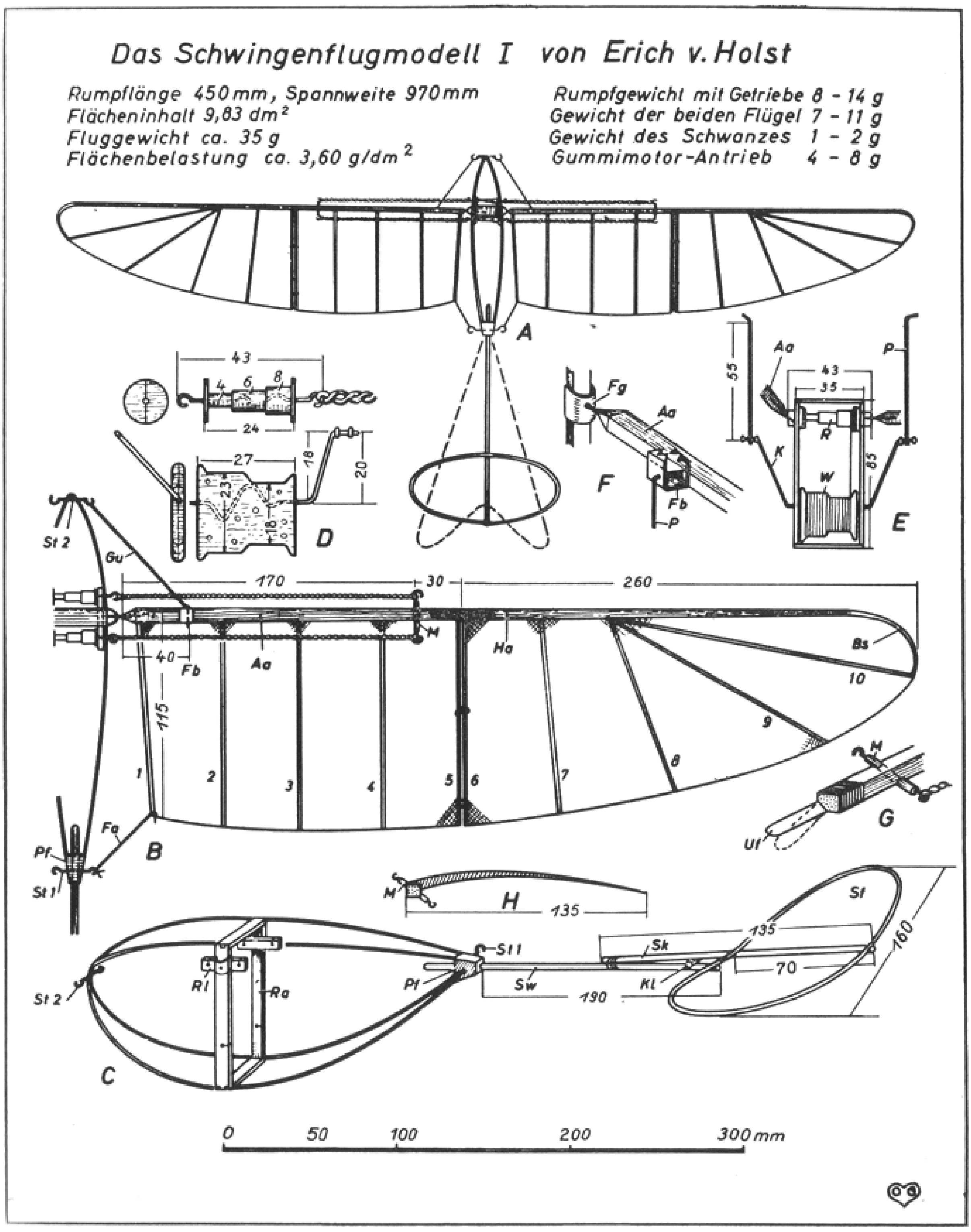
The construction starts with the main former (Ra) of the fuselage, from 7 x 2 balsa. The bearings (R1) for the thread end are made from the same material and cemented at the top of the former on the inside. The two thread reels (Fig. E) have 0·5 mm. dia. piano wire shafts, while the rollplate has one of 1·25 mm. dia. As can be seen in Fig. D the shafts are in both instances zigzagged inside to prevent any danger of turning and hence the reels and plate are best laminated during their construction of hard balsa. The ends are both reels and the rollplates are reinforced with 0·3.

The rollers and rollplate are pushed into the bearings (R1) which have slits at the top to allow this. After positioning, the slits are filled in with cement

(Araldite or UHU-hart), the rollers and rollplate freed after the cement is dry, and a bearing of properly hardened cement is achieved.

The rest of the fuselage consists of 0·8 mm. bamboo, both ends stuck into small balsa blocks. Sw is made of balsa and Sk from a straw which is bound and cemented to Sw. A small piece of balsa (K1) is pushed between Sw and Sk and fixed with a small rubber band. This allows the angle of incidence of the

Fig. 14.—The "Buzzard" by Eric v. Holst with original German text as published in "Mechanikus" magazine; all dimensions in millimetres.



tailplane Sf to be varied by repositioning of K1. The tailplane outline consists of bent grass or pampas grass, which is formed into an ellipse and cemented to Sk.

The fuselage and tailplane are covered with Japanese tissue. The wing (Fig. B) has a square spar, which acts as both L.E. and main spar. This is made from balsa and tapered towards the tip. It consists of two parts (Aa) the arm and (Ha) the hand part. Both parts are connected by a 2 mm. wide, 0·25 mm. thick watch spring strip (Uf).

At the shoulder joint the spar is sharpened to a point (Fig. F) and a small piece of piano wire cemented in. This connects into the bearing Fg which is made from tinplate.

The hooks for the rubber motors are fixed to a piece of balsa (M) which runs diagonally from the lower rear surface of the spar to the upper front surface of the spar. The connecting rods (P) are fixed to the spar through a U shaped bearing (Fb) (Fig. F).

The wing ribs 1 to 10, with the exception of 5 and 6, consist of thin bamboo or straw strips and are fixed to the L.E. only by thin gauze strips.

Rib 5 is a 2 mm. thick spruce one cemented to the end of the cross main spar. Rib 6 is also cemented to the L.E. but consists only of a strip of bamboo. Ribs 5 and 6 are fixed together by small S hooks. As the wing will not obtain its proper outline until it is covered with Jap tissue the construction is best done on a jig. After fixing the finished wing to the fuselage it is finally fixed by a rubber band (Gu) between the fuselage nose (St 2) and (Fb) and a thread (Fa) between the trailing edge and (Pf) through hooks (St 1).

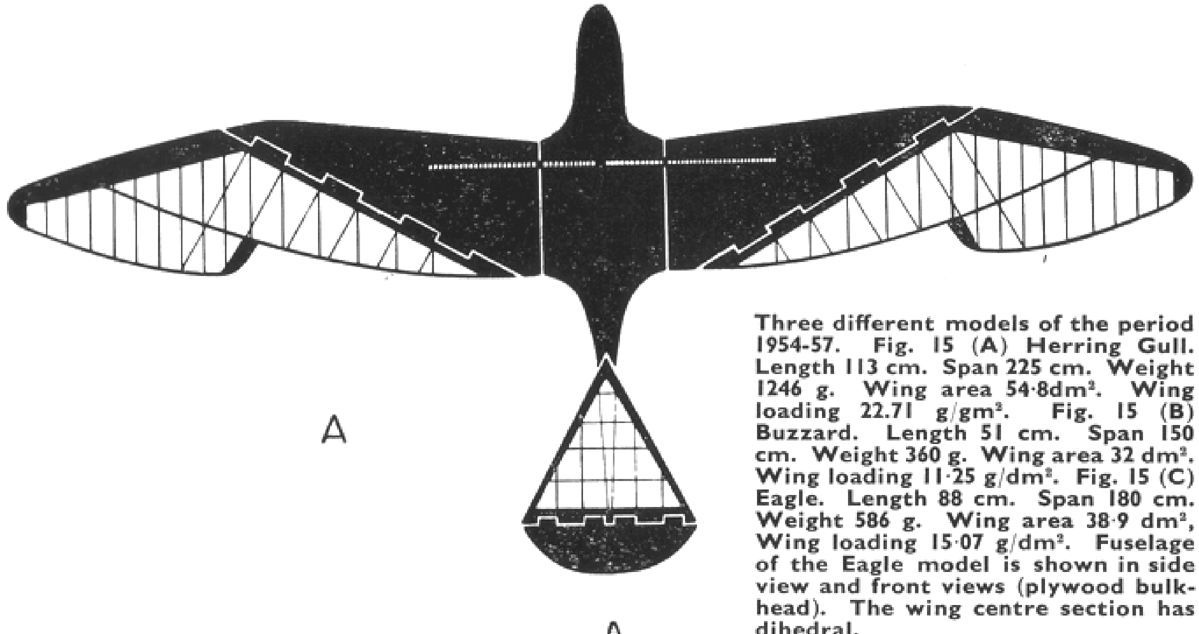
Free flight Bird models

It can be understood that the main wing spar of a bird model has to be stiff both in the direction of flight and in the direction of the flapping motion, but the wing surface itself must be flexible. With normal model wing construction the last requirement can hardly be said to be met. Hence the only way out is to divide the wing into hinged parts. The problem now is to decide how to divide the wing and along what axis. As a result of numerous experiments three types of construction were evolved. (Fig. 15.)

Model A is based on the herring gull. The slim fuselage is considerably fattened at the C.G. position and formed into a strong centre section. The wings are hinged to the centre sections on axes parallel to the fuselage axis. However as seen previously it is not enough to hinge the wings in this way as no rotation of the wing can take place along its spanwise axis and as we have seen it is this rotational motion that furnishes this forward motive power. Hence the same type of single hinge point is required as previously described. The actuation is also as described earlier. Inside the fuselage a crank drives the connecting rods to the wings. As we have both a hinged motion and a rotation of the wing root relative to the centre section and hence on the downbeat, the join will open up somewhat and close again. To avoid interference with the desired smooth flow of air a thin rubber sheet fairing is cemented over the junction.

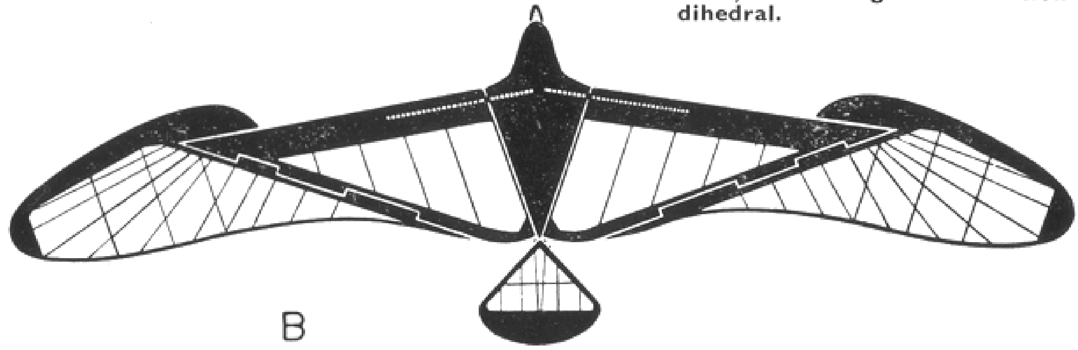
A simpler solution can be found for the hingeing of the outer wing to the inner one. As the planform of the inner wing closely resembles a right angled triangle, the required rotational effect is obtained by the hingeing over the outer wing along the base of this triangle.

When the inner wing goes up, the outer wing will move slightly down under the action of the drag. When the wing moves down however, the

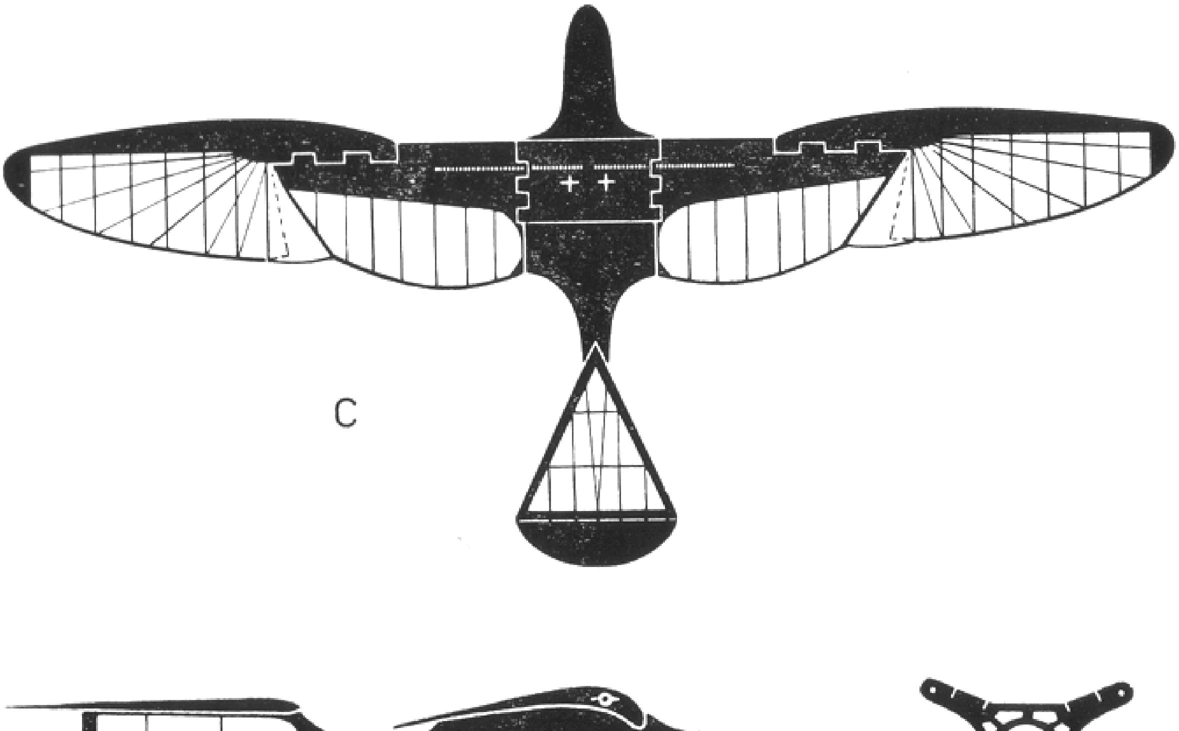


A

Three different models of the period 1954-57. Fig. 15 (A) Herring Gull. Length 113 cm. Span 225 cm. Weight 1246 g. Wing area 54·8dm². Wing loading 22.71 g/gm². Fig. 15 (B) Buzzard. Length 51 cm. Span 150 cm. Weight 360 g. Wing area 32 dm². Wing loading 11·25 g/dm². Fig. 15 (C) Eagle. Length 88 cm. Span 180 cm. Weight 586 g. Wing area 38·9 dm², Wing loading 15·07 g/dm². Fuselage of the Eagle model is shown in side view and front views (plywood bulkhead). The wing centre section has dihedral.



B



C

rotational movement furnishes the forward motive power. However as the outer wing works at an acute angle to the virtually straight working inner wing, the forward force works at an angle to the direction of flight and some part of it is cancelled out between the wing halves.

A better solution is the Wingform shown in Fig. 15B which is based on the Buzzard. Both wings have sweepback and hence the hinge between inner and outer wing is at a much less acute angle. The forward force is still not fully parallel to the direction of flight and hence there is still some loss due to the sideways component but the position is better than on Model A.

A considerable part of the improvement is due to the part of the outer wing lying in front of the inner wing.

One fault was found, namely, an airflow breakaway over the wing region where the inner wing and outer wing meet. On the wing downbeat, vortices are formed alternatively above and below the wing.

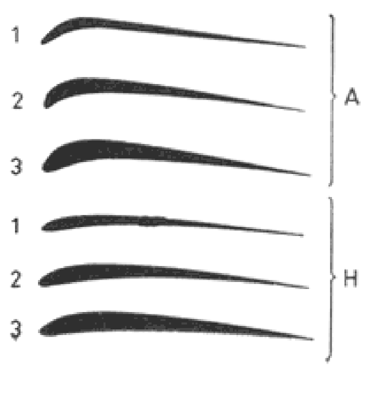
The breakaway is independent of the beat frequency but the effect is stronger on a slow beat than on a fast beat. It is obvious that on any model every effort should be made to obtain the smoothest possible airflow. The best solution was found in the Eagle model (C). As the balljoint had given difficulties on model A a different solution was tried. This consisted of a hinge, with limit stops, round which the inner wings, fixed to the centre section, were able to make an undulating motion.

In contrast to the previous model a better action was obtained from the outer wings. Part of the outer wing overlaps the L.E. of the inner wing. When the outer wing rotates on its axis, it acts as a lever, with its short arm in front and long arm behind. On the downbeat the part aft of the axis moves upwards and the part in front of the axis down. On the upbeat the reverse happens. In this way the natural action of the bird wing is fairly closely imitated.

On the Eagle model it should be possible to obtain the required rotational motion from the inner wings.

The principle seems fairly simple. The construction however is not so easy. One solution could be to make the centre movable and drive it in some way. Fig. 16A shows this with the centre section capable of rotation round a central axis. One problem remains, the axis round which the inner and outer wings rotate respectively are at right angles to each other and hence at maximum deflection a gap opens up between the wing halves. In addition the action of the inner wings should be light while that of the outer wing should be damped.

Fig. 17.—Examples of wing sections. (A) = inner wing. (H) = outer wing. 1 = Airfoil for models with span 60-85 cm. 2 = Airfoil for models with span 90-150 cm. 3 = Airfoil for models with span 160-220 cm. Fig. 18. Wing mechanism. H = wingspar with SR = steel tube. DG = universal joint. L = fixing struts. P = connecting rod. Kw = Stop for Sth and hence rotation of St (hinge axis) of the outer wing. R = inner wing rib. Rl = trailing edge.



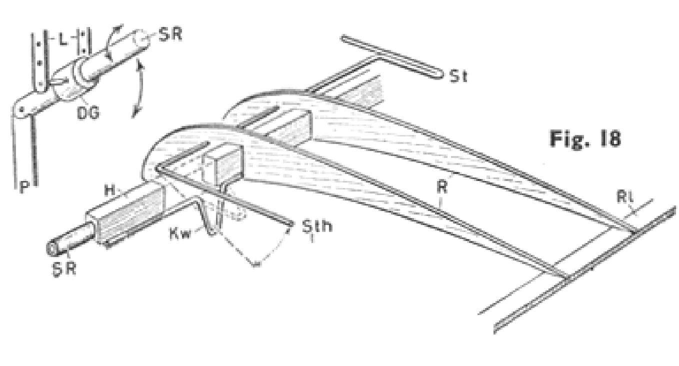
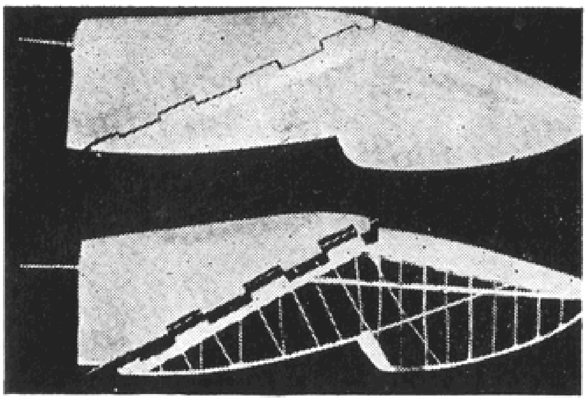


Fig. 18



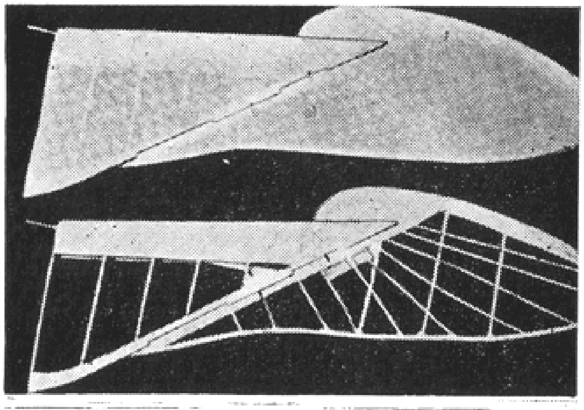


Fig. 19 above shows angled outer hinger Herring Gull. Fig. 20 above right is Buzzard shape and Fig. 21 at right, the Eagle. Refer to Fig. 15.

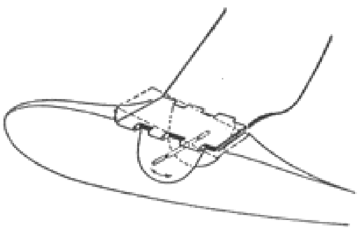
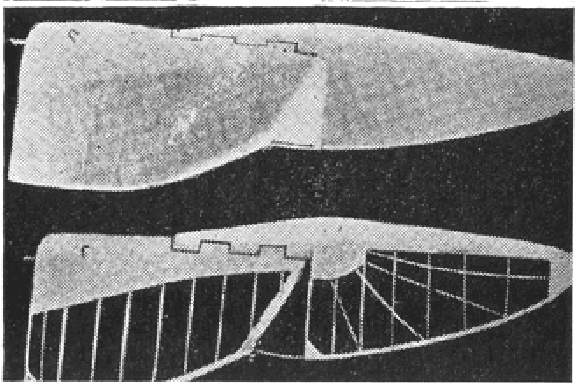


Fig. 16. — Proposed solution for obtaining rotation at wing root.



Both difficulties can be overcome by fixing a flexible division between the inner wing and the outer wing.

Test flights have proved that model C is superior to A and B in powered flight. A and B are however better in gliding and for thermal flight. As the wing is constantly moving sufficient thought must be given to the distribution of weight. As we move out to the wing tip the weight must get less and less.

The wing profiles of the inner wing should be much more cambered than those of the outer wings (Fig. 17 A and H). For smaller models a higher cambered aerofoil is best, for larger models less camber is required. The most important difference between the aerofoils of the inner wing compared to that of the outer wing is that for the inner wing the nose droops strongly down while for the outer wing a more normal aerofoil is required. The outer wing has 3° of washout built in.

Control functions

The angle through which the outer wing should be able to turn must be controlled. On my models I used wire pieces which are fixed to the outer wing and protrude into the inner wing where they are limited by vernier screws. On model C especially it is necessary to have a limiting device as the rotation is obtained indirectly. However there is still one disadvantage as the limiting device only works during the motor run. During the glide the outer wing should however be fixed at its optimum angle of incidence. A possible solution is given in Fig. 18. Here the axis is used for control. It consists of 2 mm. piano wire with the free end bent through 90° (St). The other end runs over the hinge between the inner and outer wing. In this way a small lever is formed through which the outer wing rotation can be limited. The top stop is the wingspar which is also the correct incidence for the glide. Rubber bands which pull the lever up see to it that the glide position is automatically achieved as soon as no stronger forces oppose it. The action depends on using the hinge as a torsion bar.

On the wing downbeat the bent over end hits the wing spar. The wing drag works especially on the aft portion of the outer wing which will try to deflect upwards. It works against the torsion of the hinge which increases on an increase of the deflection and so gives a progressive stamping. As soon as the wing is on the upbeat the drag works on the top surface of the outer wing and this will deflect downwards. The only counteracting force is now the rubber band. The bottom stop consists of Kw which can be altered at will by hand and which limits the wing deflection.

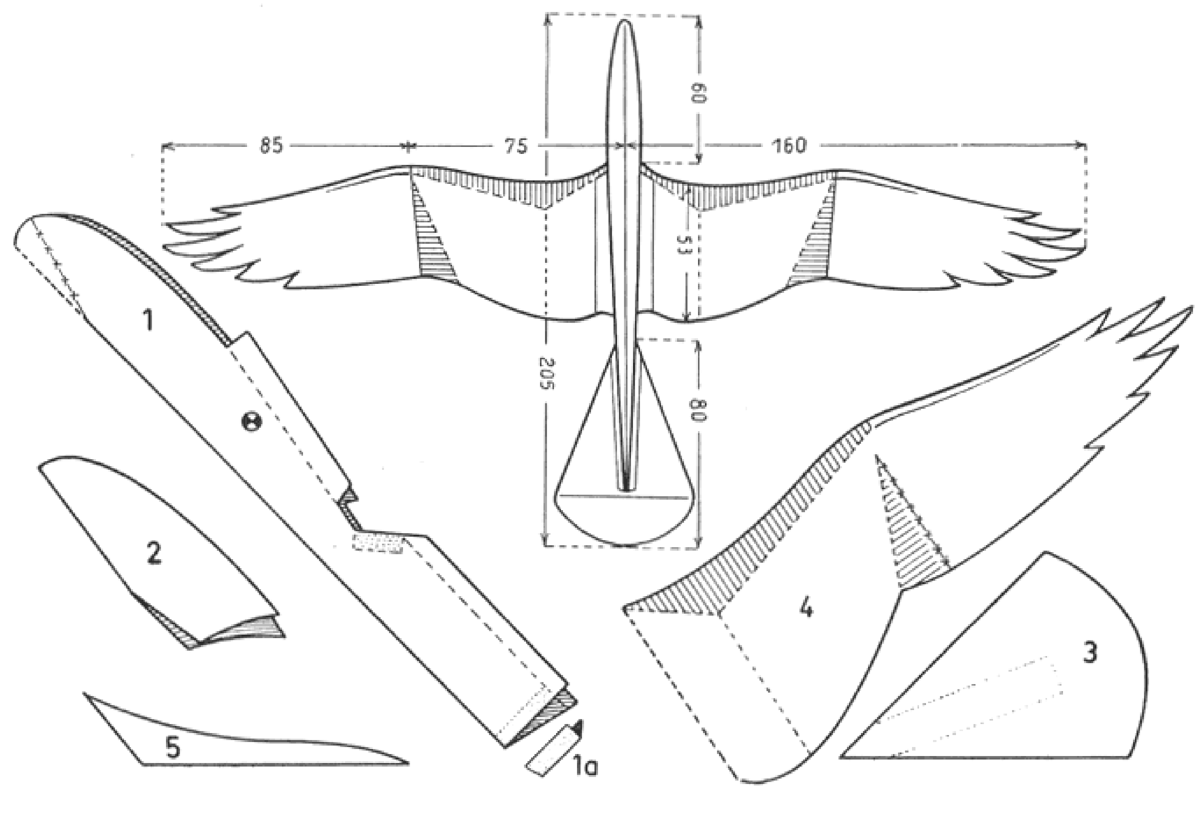
From a series of experimental models, built to assess which wing planforms and proportions were best, the model shown in Fig. 21 showed most promise.

In Fig. 22 a small experimental model is shown made from stiff drawing paper. With a model of this type experiments to assess the optimum angles of incidence are simple to carry out.

First of all the model is adjusted for straight flight. After that the model can be adjusted for other types of flight paths (Fig. 23). The dihedral of the outer wing is adjusted between $+3°$ and $+5°$. With the outer wings at $0°$ angle of incidence straight flight is obtained. When the left outer wing is turned so as to lower the nose and hence raise the trailing edge and turn to the right is achieved (Fig. 23a). If one decreases the angle of incidence of both outer wings the model will fly straight but faster and with a steeper glide angle.

These alterations of the flight path occur only when the angles of incidence are changed up to approximately $-5°$. If this value is exceeded on one wing the lift will break down and the wing on this side will go down. The opposite effect occurs when the outer wing is adjusted so that the wing L.E. is up and the T.E. down. In this case the wing is braked by the action of the air-

Fig. 22.—Rook shape model to be made from drawing paper or similar.



stream and lifted up (Fig. 23C). When the left outer wing has a negative incidence but a positive angle of attack the model will turn left but due to the combination of the wing lifting and braking actions a negative turning movement exists which causes an unstable motion. A positive incidence of the left wing will however result in a smooth right hand turn (Fig. 24A).

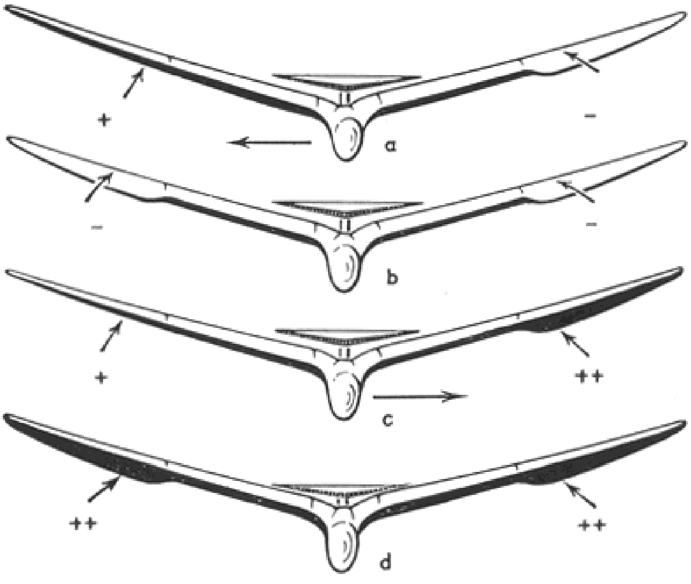


Fig. 23.

A strong positive incidence of both wings will result in a landing flap action (Fig. 23d). On ornithopters the climb, turning and control of the forward speed can be achieved solely by alteration of the angle of incidence of the outer wings. Obviously experiments of this nature are only of use for the gliding flight as during powered flight much larger variations of the incidence occur without any great effect on the flight path.

During the powered flight the angle of attack varies between $+20^\circ$ and -12° without airflow breakaway. This is due to the fact that during the powered flights the model moves forward so that different forces come into effect than during the glide.

As is known the performance of an ornithopter during the power run is greatly dependent on the rotation of the outer wing. On the Eagle model (Fig. 15c) a system was evolved through which this rotation could be regulated by means of a control arm. The same mechanism was used on the model in Fig. 21. When the rotation is limited to a small value a strong wing beat is obtained which results in a fast straight flight over a considerable distance. When the rotation has a greater value a steep climb is achieved.

Hence a choice must be made between the two and so far it has not yet been possible to develop a wing, which will automatically attain its optimum performance as a function of the wing beat frequency. However I feel a solution should be possible. It has often been thought that the circling flight of a bird was due to one wing beating faster than the other. That this is not so was proved by E. von Holst in 1943 when he tested a model on which only one wing could move.

As long as the model was held in the hand the movable wing beat through 90° while the other stood still. However as soon as the model was released both wings beat through 45° and the model flew straight. Although only one wing was driven the other wing moved in sympathy with identical frequency.

Hence it can be deduced that both during the power runs and during the glide any turns are the result of changes of angle of incidence on the outer wings. Fixed rudders which I tried on some of the models did not produce any change in course.

A steep climb or even hover flight which E. von Holst obtained on some of his models are possible with my models. I hope that many more aeromodellers will turn their attention to this fascinating aspect of model flight which will undoubtedly advance the results very much.