Odonatologica 7 (1): 49-58 *March 1, 1978*

AERODYNAMIC PROPERTIES OF *LIBELLULA QUADRIMACULATA* L. (ANISOPTERA: *LIBELLULIDAE*), AND THE FLOW AROUND SMOOTH AND CORRUGATED WING SECTION MODELS DURING GLIDING FLIGHT

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Received and Accepted August 2, 1977

Polar curves of single wings and paired ipsilateral wings of *L.quadrimaculata* and of the whole animal in gliding flight posture at two Reynolds numbers are presented. All curves are distinguished by their rather level climax at maximum lift coefficient. Display of flow around wing section models compared with smooth models exhibits an effect of corrugation only at high Reynolds numbers and great angles of attack not relevant for gliding flight.

INTRODUCTION

Gliding flight without wing flapping is common in birds, but among insects only members of the Orders Odonata and Lepidoptera are capable of soaring or gliding flight. In the European dragonfly fauna most members of the family Libellulidae perform gliding flight, but some Aeshnidae do as well. I watched one *Anax imperator* Leach (Aeshnidae) and one *Libellula quadrimaculata* L. (Libellulidae) performing gliding flight against a faint wind which compensated the animals' thrust, so that they stood still in the air for seconds. HANKIN (1921) stated that some species of Odonata, especially those with enlarged hind wings like *Rhyothemis*, perform soaring flight for hours almost without any wing flapping.

With regard to this, dragonfly wings seem to have good aerodynamic properties. From the view of conventional aerodynamics this appears surprising since in gliding flight the wings of a dragonfly approach the lower end of the range of Reynolds numbers where ordinary aerofoil action deteriorates rapidly. Aerodynamic properties can be estimated either by constructing the polar curve after measuring lift and drag in a wind tunnel, or by displaying the flow pattern around the wing. The wings of several Lepidoptera (NACHTIGALL, 1967), of *Drosophila virilis* (VOGEL, 1967), of *Ephemera vulgata* (BRODSKI, 1970), and of *Calopteryx splendens* (RUDOLPH, 1976) have already been tested in a wind tunnel. They turned out not to have good properties in the sense of technical aerodynamics since they did not reach mean lift coefficients of aerofoils, and their drag coefficients exceeded those of aerofoils. Their only valuable character is that separation of flow is delayed up to much greater angles of attack than a technical aerofoil would endure. This is clearly indicated by the polar curve of an insect wing, which shows a remarkable plateau at maximum lift coefficient.

It is commonly stated that for an aerofoil the most convenient outer shape is that of a smooth streamlined profile. Insect wings do not, however, have smooth profiles. BRODSKI (1970) has shown the polar curve of a real corrugated wing of *Ephemera vulgata* to be significantly more advantageous than that of a flat plate of equal dimensions. From this he deducted that the better aerodynamic properties of real wings might be attributed to boundary layer turbulence caused by the rough corrugated wing surface.

There are some particular differences between the aerodynamics of aeroplane and insect wings. It is well known that at medium Reynolds numbers of bird flight and model aeroplane flight a turbulent boundary layer greatly reduces total drag and extends the range of effective angles of attack, while at the high Reynolds numbers of technical aerofoils a turbulent boundary layer disproportionately increases the frictional drag. At the medium Reynolds numbers with smooth wing surfaces no spontaneous transition from laminarity to turbulence will occur, which consequently is provoked artificially by a sharp profile-nose, by protruding feathers or other roughness elements. At the far lower Reynolds numbers of an insect wing in gliding flight the boundary layer beginning at the stagnation point with no exception is laminar at first, but it was suggested that the scales of butterfly wings or the pleats of other insect wings might cause transition.

It must be mentioned that assuming the steady-flow regime in the experiments with the wings of *Drosophila*, *Ephemera*, and *Calopteryx* natural conditions were altered appreciably, for these three insects never glide without flapping wing. During a flap rapid and continuous changes of flow velocity, angle of attack, and Reynolds number are to be noticed. The latter increases gradually from wing base to tip during the stroke. Only JENSEN (1956) made sure that this gradient was established in his measurements on the wings of *Schistocerca gregaria*, and he found greater lift coefficients and smaller drag coefficients than in all other insect wings tested so far. So it must be emphasized that wind tunnel experiments without establishing that gradient may be applied only to insects performing gliding flight.

The results of some experiments are presented here which aimed to quantify, in comparison to other insects the aerodynamic properties of the dragonfly *Libellula quadrimaculata*, a species capable of gliding flight. Polar curves of single wings and the whole insect were constructed, and the theoretically postulated effect of wing pleating was ascertained.

METHODS

The flow pattern around enlarged wing section models of *L.quadrimaculata* were tested in a water channel. In addition a flat plate and a smooth profile were used. The latter was formed by drawing a smooth envelope through the corner points of a corrugated wing section. Two fore wing sections were used as a template for building models: one immediately distal of the triangle, and one half way between the nodus and the proximal edge of the pterostigma. The main wing veins formed the corner points of the models which were made of 2 cm wide rectangular strips of 0.3 mm thick sheet-iron with 4 or 8 cm chord length.

The perspex water channel (150 cm x 15 cm x 10 cm) was placed between double rails on which a bridge-like carriage was towed over the channel by an electric motor. A wing model was pivoted into a socket on a support from the rear of the carriage, so that it penetrated the water surface from beneath. On top of the carriage a camera was mounted vertically facing the wing model. Thus the camera was fixed with respect to the wing model moving through still water. The streamlines around the models were displayed by chalk dust spread upon the surface.

For the sake of comparison the Reynolds numbers with a real wing and a model had to be identical. Since the dimensionless Reynolds number is calculated as

$$\mathrm{Re} = \frac{Vl}{\nu},$$

(where V = velocity of flow, l = chord length, and ν = kinetic viscosity of fluid), the Reynolds number of gliding flight in dragonflies could be maintained in the water channel experiments by adjusting the carriage velocity according to the greater model chord length and the lesser kinetic viscosity of water with respect to that of air. Experiments were performed at various Reynolds numbers from 2400 to 150, corresponding to gliding flight velocities from 340 $\mathrm{cm.sec^{-1}}$ to 20 $\mathrm{cm.sec^{-1}}$. Reynolds numbers over about 600 are not relevant for gliding flight, and are chiefly of interest from a comparative standpoint.

Lift and drag forces depending on the angle of attack were measured mechanically on single wings, paired ipsilateral wings, and dried animals in gliding flight posture in a wind tunnel as described by NACHTIGALL (1967). All force measurements were transformed into the dimensionless coefficients of lift (C_L)

and drag (C_D). Polar curves were constructed by plotting C_L against C_D with the angle of attack treated parametrically.

RESULTS

As an obvious feature the polar curves of single wings and paired ipsilateral wings of *L.quadrimaculata* and of the whole animal show a rather level climax at angles of attack near 30° to 35° (Figs. 1, 2). With the wings of *Calopteryx splendens* this plateau is even more pronounced (RUDOLPH, 1976). From this characteristic one may draw the conclusion that separation of flow is delayed, and stall does not occur abruptly. This should be confirmed by displaying the flow pattern around wing models.

In any anisopterous species the polar curves of force and hind wing show particular differences which are due to their dissimilar size rather than to an insignificant variation in corrugation. Lift is greater in a hind wing because of its greater surface area, but lift increases less than surface area does. Thus the maximum lift coefficient in a hind wing is exceeded by that of a fore wing (Fig. 1). The polar curves of a wing pair and the whole animal resemble very much that of the better single wing, which is remarkable if the flow around a wing pair, suggesting a negative effect of the slotted wing construction during gliding flight, is taken into account. Comparison of polar curves at various Reynolds numbers reveals decreasing lift coefficient with decreasing Reynolds number, while the plateau is not seriously affected (Fig. 2). This is true for the whole animal as well as for single wings. Obviously polar curves of dragonflies take a medium position between those of *Schistocerca* and *Drosophila*.

Figures 3-5 show the flow around enlarged wing section models at certain Reynolds numbers. Flow at other Reynolds numbers is either identical or shows an intermediate regime among the extreme numbers presented here. In all figures flow is from right to left.

At high Reynolds numbers (2400 and 1200) the flow around the flat plate with 8 cm chord length resembles very much that described by MOORE (1959) as the Wallis's hypothesis for thin aerofoil with rounded nose at extremely great Reynolds numbers (1×10^6) based on chord length. The only difference is that with the flat plate at moderate and high angles of attack the boundary layer is laminar only from the stagnation point to the sharp front edge, where transition and turbulent separation take place at sufficiently high Reynolds numbers (Fig. 3a). Thus behind the leading edge a separation bubble is formed, encircled by wholly turbulent flow reattaching just downstream, and at moderate to high angles of attack again separating a short distance behind the reattachment point. The downstream separation point moves forward with increasing angle of attack until it reaches the reattachment point, causing burst of the separation bubble, i.e. stall. This is considered a comparatively good flow pattern, since stall does

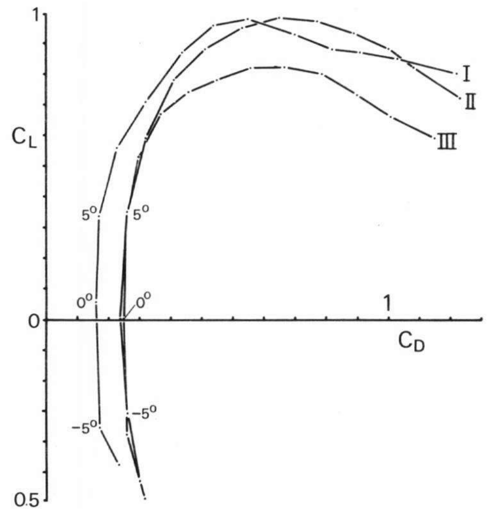

Fig. 1. Polar curves of *Libellula quadrimaculata* at a Reynolds number of 640: (I) pair of ipsilateral wings in one plane: – (II) fore wing; – (III) hind wing.

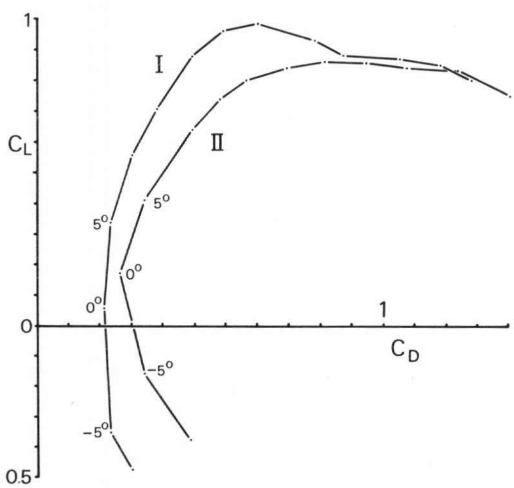

Fig. 2. Polar curves of a whole *Libellula quadrimaculata* male with wings stretched out horizontally in one plane: (I) Reynolds number 640; – (II) Reynolds number 320.

not occur except at rather great angles of attack.

With decreasing Reynolds number (Fig. 3b, d) transition is more and more reduced even at moderate to high incidence. Formation of a separation bubble with reattaching flow is thus impeded. A comparatively broad wake containing a slight bound vortex at the trailing edge is left behind the plate, increasing total drag. Figures 3c, d elucidate that at a small angle of attack no nose bubble is formed, and that at a high Reynolds number (Fig. 3c) the flow adheres still better than at a low Reynolds number, where still a weak bound vortex can be seen at the trailing edge (Fig. 3d).

So we may conclude that, in the sense of conventional aerodynamics, a flat plate of the order of size of an insect wing would be an efficient type of wing at all angles of attack except at high Reynolds numbers outside the range of that of gliding flight. At smaller Reynolds numbers appropriate to gliding flight there is still a rather broad wake resulting from non-reattachment and increasing total drag even at small incidence.

Using corrugated wing section models stagnant or swirling fluid appeared to fill the

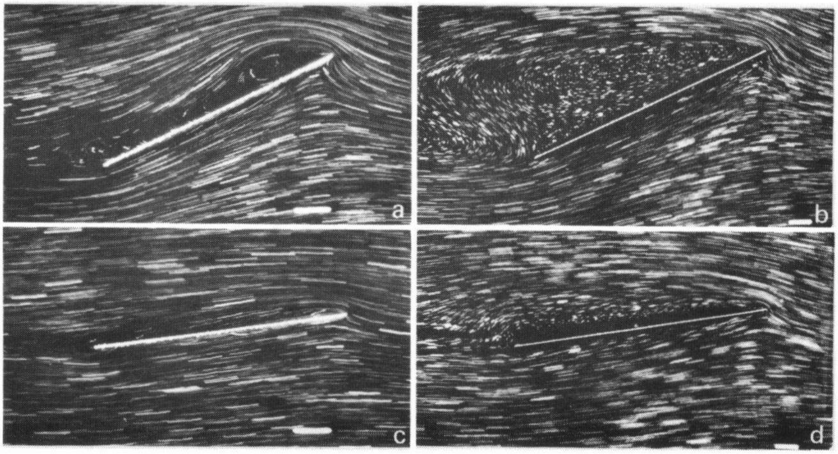

Fig. 3. Flow (from right to left) around a flat plate in relation to Reynolds number and angle of attack: (a,c) Reynolds number 1200; – (b,d) Reynolds number 150; – (a,b) angle of attack 25°; – (c,d) angle of attack 8°.

folds up to the corner points, thus forming a regular smooth "surface" along which the outer streamlines were passing. So it was assumed that the corrugated wing actually worked as a smooth profile, but a smooth profile proved to show relatively poor flow pattern at all Reynolds numbers tested (Fig. 4). Stall commences already at moderate angles of attack but not within the range of angles convenient for gliding flight. Probably the boundary layer remains laminar at the rounded nose even at high Reynolds numbers, thus being prevented from reattachment. At small angles of attack a wake of equal dimensions as with the flat plate is established, so an evident advantage of the smooth profile compared with the flat plate cannot be revealed within the range of small Reynolds numbers and angles of attack.

Quite different results are obtained with a proximal and a distal wing section model. At high Reynolds numbers with the proximal section, stall occurs already

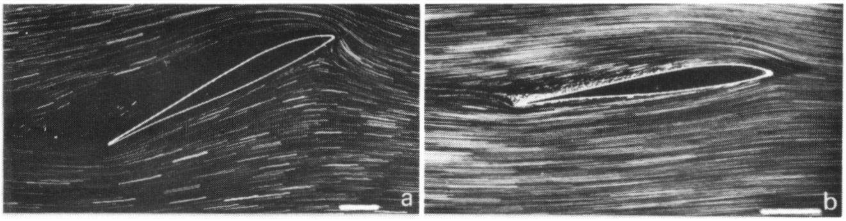

Fig. 4. Flow (from right to left) around a smooth profile: (a) Reynolds number 1200, angle of attack 25°; – (b) Reynolds number 320, angle of attack 8°.

at moderate angles of attack (near 15°), though transition is likely to begin at the costa (Fig. 5a). There is a continuous transformation of flow pattern down to small Reynolds numbers, where flow still adheres if the section is set at the same incidence (Fig. 5b), though a faint bound vortex is formed at the trailing edge. Within the range of smaller angles of attack (less than 15°) the proximal section works equally well at all Reynolds numbers.

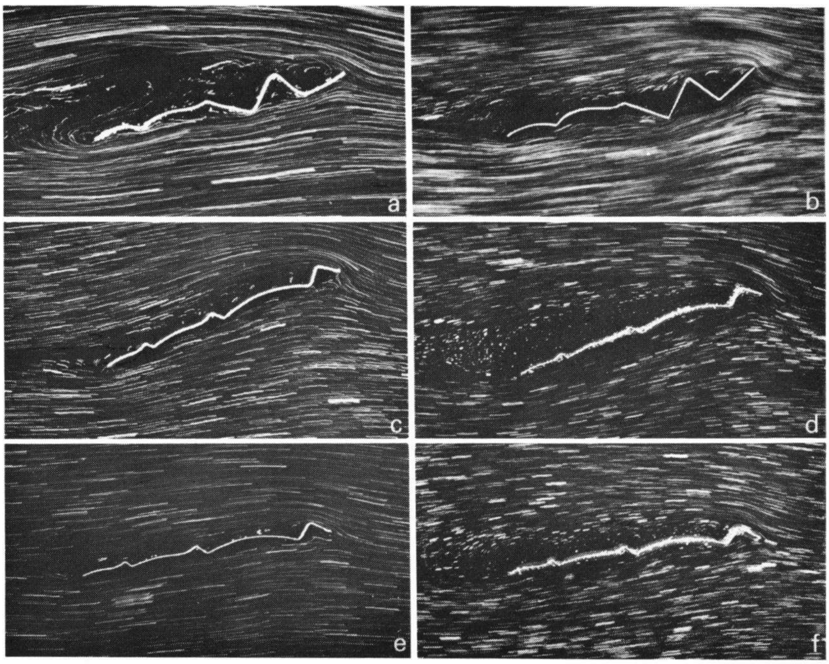

Fig. 5. Flow (from right to left) around two corrugated wing section models of *Libellula quadrimaculata* in relation to Reynolds number and angle of attack: (a, c, e) Reynolds number 1200; – (b) Reynolds number 320; – (d,f) Reynolds number 150; – (a,b) angle of attack 15°; – (c,d) angle of attack 20°; – (e,f) angle of attack 10°.

As previously shown (RUDOLPH, 1977), at high Reynolds numbers with the distal wing section the flow adheres up to extremely great angles of attack (Fig. 5c) which are not used in gliding flight. Transition will commence at latest at radius 1, where the flow separates. At moderate and great angles of attack the depression behind radius 1 is filled with a fluid mass swirling counterclockwise. The separated flow reattaches downstream of this separation bubble. Thus, at high Reynolds numbers the flow around the distal section, too, resembles that described by the Wallis's hypothesis. As with the proximal section there is a continuous transformation of flow down to small Reynolds numbers, where unexpectedly stall is complete already at an incidence near 20° (Fig. 5d). Even at those small angles of attack convenient for gliding flight the distal section shows a better flow at a high Reynolds number (1200) (Fig. 5e) than at a low Reynolds number (150), where a broader wake is established (Fig. 5f). Thus the proximal section shows efficient flow already under conditions of gliding flight, while the distal section is more efficient at high Reynolds numbers.

CONCLUSIONS

At least three parameters of the outer shape of a corrugated wing section are likely to influence the flow pattern:

(1) The ratio of profile height to chord length. In a distal wing section of *L. quadrimaculata*, where the quotient profile height/chord length is 12.3, the flow is influenced in an advantageous manner as seen from the standpoint of conventional aerodynamics, while at a proximal wing section, where the quotient is only 6.14, there is a detrimental effect already at moderate incidence. This holds only for high Reynolds numbers. At small Reynolds numbers the effect is the inverse.

(2) The angle made up by the costa, radius 1 and radius 2 opens downward distal to the nodus (Fig. 5c), while in proximal wing regions the angle made up by the costa, subcosta, and radius is of the same order of size but opens upward (Fig. 5a). In the latter case the stagnation point lies at the narrow plate between the costa and subcosta; in the former case it is immediately at the costa at small angles of attack or somewhere inside the first fold, but not in contact with the model at moderate to high angles of attack.

(3) The distance from the leading edge to the point of maximum profile height, which is much shorter in a distal wing section than in a proximal section.

No reasonable interpretation of the different flow patterns at distal and proximal wing sections can be given so far but flow around corrugated wing sections seems to be in good accordance with the polar curve of the fore wing (Fig. 1 I). Probably the slight bow near the climax of the curve is due to the fact that, at those angles of attack, stall does not occur at the same time along the whole span.

The flow around paired sections of ipsilateral wings is heavily impaired by the jet passing vertically to the upper side through the slot between both sections, thus forcing the oncoming streamlines of the fore section outward. Separation occurs at least in the leading section at all Reynolds numbers, even at small angles of attack. This is in contrast to the polar curve. The only apparent reason for this discrepancy is found in the experiments of REES (1975) with a wholly submerged corrugated wing model of *"Syrphus balteatus"* (Diptera: Syrphidae). These suggest that, at small Reynolds numbers, in regions near the wing model tips separation is delayed up to great angles of attack (35°) by high velocity fluid passing around the wing tip into the boundary layer on the upper surface, thus preventing the stall-eliciting stagnation of the boundary layer. Such high velocity fluid originating in the tip vortices might deflect the slot-jet downstream. This view is supported by the results of my own experiments with real wing pairs in a wind runnel (in preparation).

The experiments illustrated the effect of corrugation on the flow around wing section models of a dragonfly, compared with smooth models. It was assumed by BRODSKI (1970) and RUDOLPH (1976) that typical aerodynamic properties of insect wings were due to turbulence caused by the corrugation penetrating the boundary layer from beneath. However, the formula used by Brodski and Rudolph to calculate the boundary layer thickness at an insect wing applies only to flat plates at zero angle of attack, and therefore is of little use in the problem we are involved with. Moreover, the effect is not uniform throughout the various types of corrugation met with in real wings. Owing to the small dimensions of the models it has not been possible to determine by direct observation whether the boundary layer is turbulent or laminar. However, turbulence, if it does occur, is likely to commence at sufficiently high Reynolds numbers already at the costa or radius 1, where the flow separates, rather than somewhere along the chord. At the smallest Reynolds numbers (150) only laminar separation will be possible at the veins and no transition will occur at all. Those stagnant or swirling fluid masses trapped in the folds even up the wing surface, making the corner points ineffectual with respect to the boundary layer.

A valuable effect of corrugation on flow occurs only at high Reynolds numbers which are quite relevant for flapping wings. In the range of small Reynolds numbers and angles of attack during gliding flight, the corrugation of a dragonfly wing is not to be considered as advantageously influencing the flow, and the wing might as well be replaced by a flat plate or a smooth profile. However, when under load during the stroke, an extremely thin wing with such a long span as in dragonflies needs an excess in spanwise stiffness, which is conferred only by corrugation.

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