28. On the Aerodynamics of Separated Primaries in the Avian Wing.

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ABSTRACT

The narrowed vane parts of the outer primaries, which in many bird species separate from each other when the wing is stretched, and which are referred to briefly as "separated primaries", were studied for their aerodynamic performance under conditions of steady state gliding by means of a simplified model calculation. It was thought that the separated primaries may cause reduction of induced drag, provided that the lift coefficient is equal to that in the inner unsplit wing. However, reduction of total drag and a resulting improvement in gliding performance is predicted to occur only with larger birds, if at all, since the Reynolds number of the flow past the separated primaries of smaller birds is low enough to cause an increase of profile drag. Reduction of drag by separated primaries will increase with their number in a given wing, with their area relative to the total wing area, with the lift coefficient of the wing, and with decreasing aspect ratio. In principle, these corre-lations also apply to non-accelerated powered flight, where a possible reduction of drag in the distal segment of the wing could increase the forward thrust of the down-stroke. Studies into wing geometry and profiles of separated primaries in several bird species suggest that their main functional importance does not in fact lie in drag reduction, which is expected to occur only under certain conditions, with the absolute size of the animal concerned playing a substantive role. The suggestion that their principal function is to increase the total lift coefficient turns out to be much more plausible.

INTRODUCTION

The outer primaries in the completely stretched wing are usually separated in most bird species. In such primaries the distal part of the vane is more or less narrowed in comparison to the proximal part which remains covered by the overlapping rear primaries. Adhesive or frictional surface characteristics (Sick[12]), typical of the proximal part where they keep the feathers together to form one coherent wing surface, are absent from these distal parts. It is tempting to assume that these "separated primaries" might have a particular functional role. Their usual characterisation in terms of aerodynamics and aeromechanics is based on a proposition originally made by Graham.[1] The split distal segment of the wing is thought to act as a high-lift device (slotted wing system) and to reduce the induced drag of the wing.

Wing slots have several applications in aviation. The auxiliary wing of an aircraft, employed for lower flight speeds and for take-off and landing on short runways, is one of the known variants in this context. The component wings are arranged very close to one another in such a slotted wing. The alula will form such a system with the inner part of the distal wing segment, as originally assumed by Graham[1] and more recently confirmed by experimental studies (Nachtigall and Kempf[4]). Yet, circumstances are different in the separated primaries. They can be thought of as independent wings since they are separated by half to one full chord length. Hence, a Handley–Page–Lachmann effect will be less probable in the context of gliding or soaring flight or of the downstroke in unaccelerated horizontal powered flight. The extent to which the drag of the wing can be brought down will be the subject of this study, conducted with reference to absolute wing size.

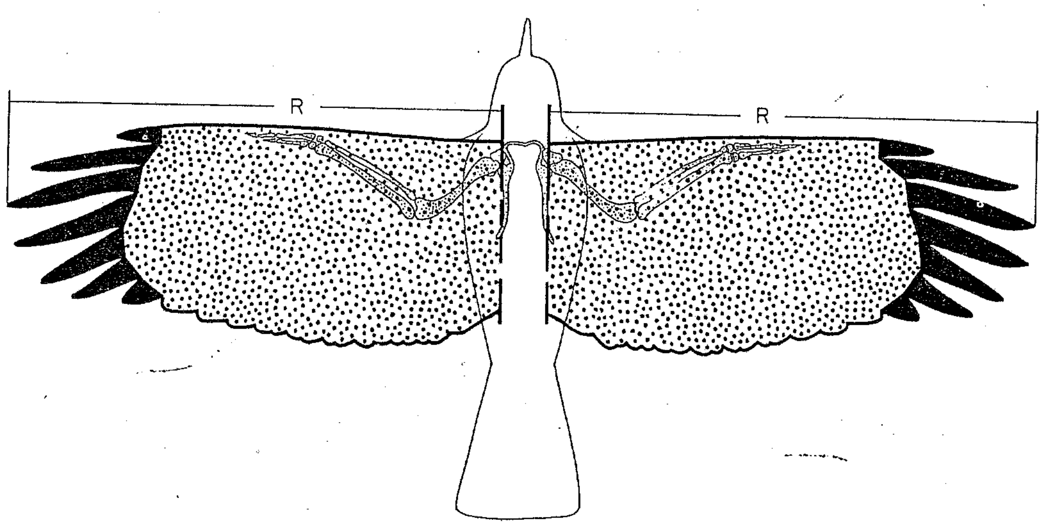

FIG. 1. Principles to determine characteristic dimensions of wing geometry; "span" $2R$, unseparated wing area S_1 (dotted), area of separated primaries S_2 (black), total wing area $S = S_1 + S_2$, fractional area of separated primaries $y = S_2/S$, aspect ratio $A = 4R^2/S$. Note that the "wing span" in this context is less than the distance from wing tip to wing tip which is the wing span used in aeronautics. The reason is the difficulty of measuring the total wing span of a sacrificed bird with sufficient accuracy, while precise values of the wing length R can be easily obtained.

MATERIAL

Serial measurement was applied to 13 fairly common species, with the view to deriving an average wing representative of each. The equipment used and the photographic techniques will not be expounded in this paper, as they have been described in the context of earlier investigations (Oehme,[6, 7] Oehme and Kitzler[8]). The dimensions needed for adequate treatment of the problem were obtained by the principles given in Fig. 1. Profile shapes

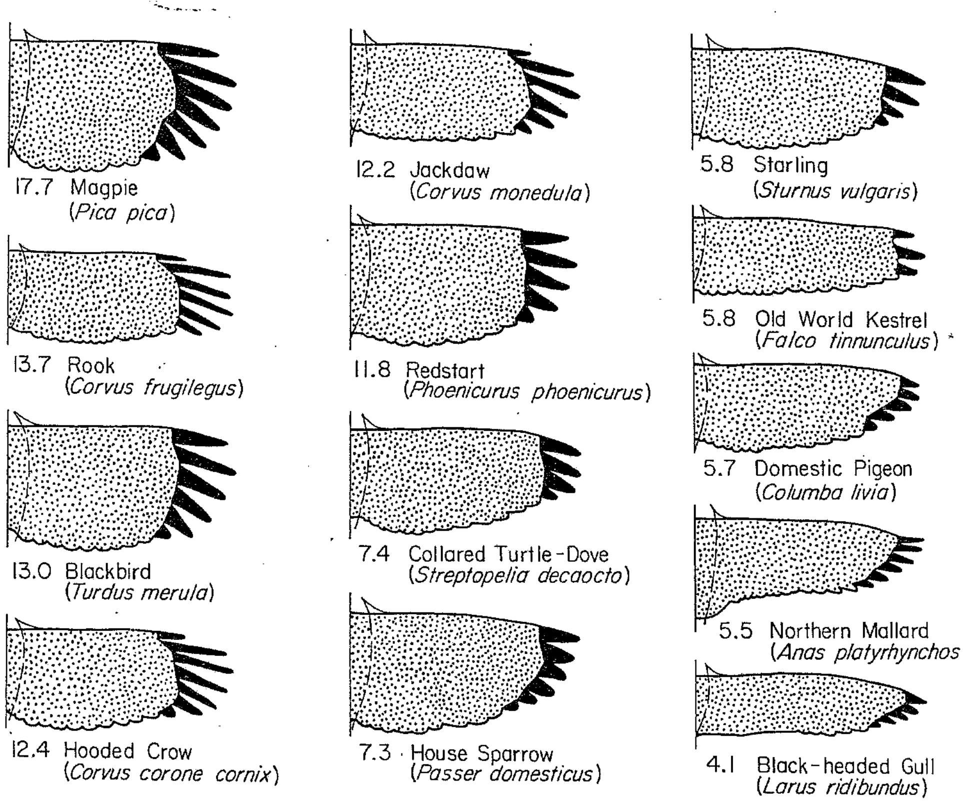

FIG. 2. Wing outlines of 13 species, redrawn to equal dimension of R. The value of $100y$ is added.

and structure of the separated primaries were determined as follows. The narrowed part of the vane was cut across centrally and perpendicularly to the rachis, with a sharp razor blade. Photomicrographs were taken from the cut surface in incident light. The cross-sections of the feathers remained unchanged by application of this technique, unlike wax or paraffin imbedding which regularly caused cross-sectional deviation. No attempt was made in the context of this study to find out if and to what extent a given profile camber of separated primaries may be changed in flight, as observed from profiles of the inner non-split wing (Nachtigall and Wieser[5], Oehme[7]).

Different Wing Shapes

A comparison of the wing shapes, given in Fig. 2, shows that the number of separated primaries and the fractional area of the split distal wing segment, $y = S_2/S$, vary within fairly wide limits. No regularity could be found, according to Fig. 3, for correlating y to data of aeromechanical relevance.

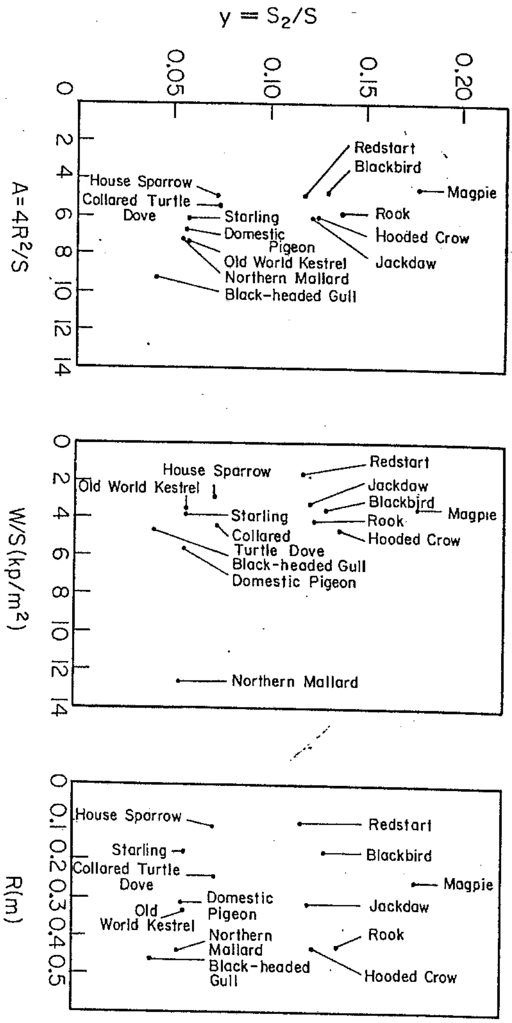

FIG. 3. Fractional area of separated primaries (y) plotted against aspect ratio (top), wing loading (middle), and wing length (bottom).

Consequently, no simple morphologico-functional interpretation will be possible of the wing structures under review. Such a situation seems to support the idea of studying the aerodynamic peculiarities of the "separated primaries" phenomenon.

DRAG OF A WING WITH OUTER PARTS SPLIT INTO TANDEM WINGS

Let us first elaborate briefly on what is called the tandem effect (Fig. 4). Assume an untwisted airfoil (area S, span $B = 2R$) with continuous profile and elliptic outline and, consequently, an elliptic distribution of lift. Then both lift and induced drag are determined by the air speed and the angle of incidence. Suppose that the airfoil is subdivided into two tandem wings, equal in size and positioned one behind the other, and with span equal to that of the

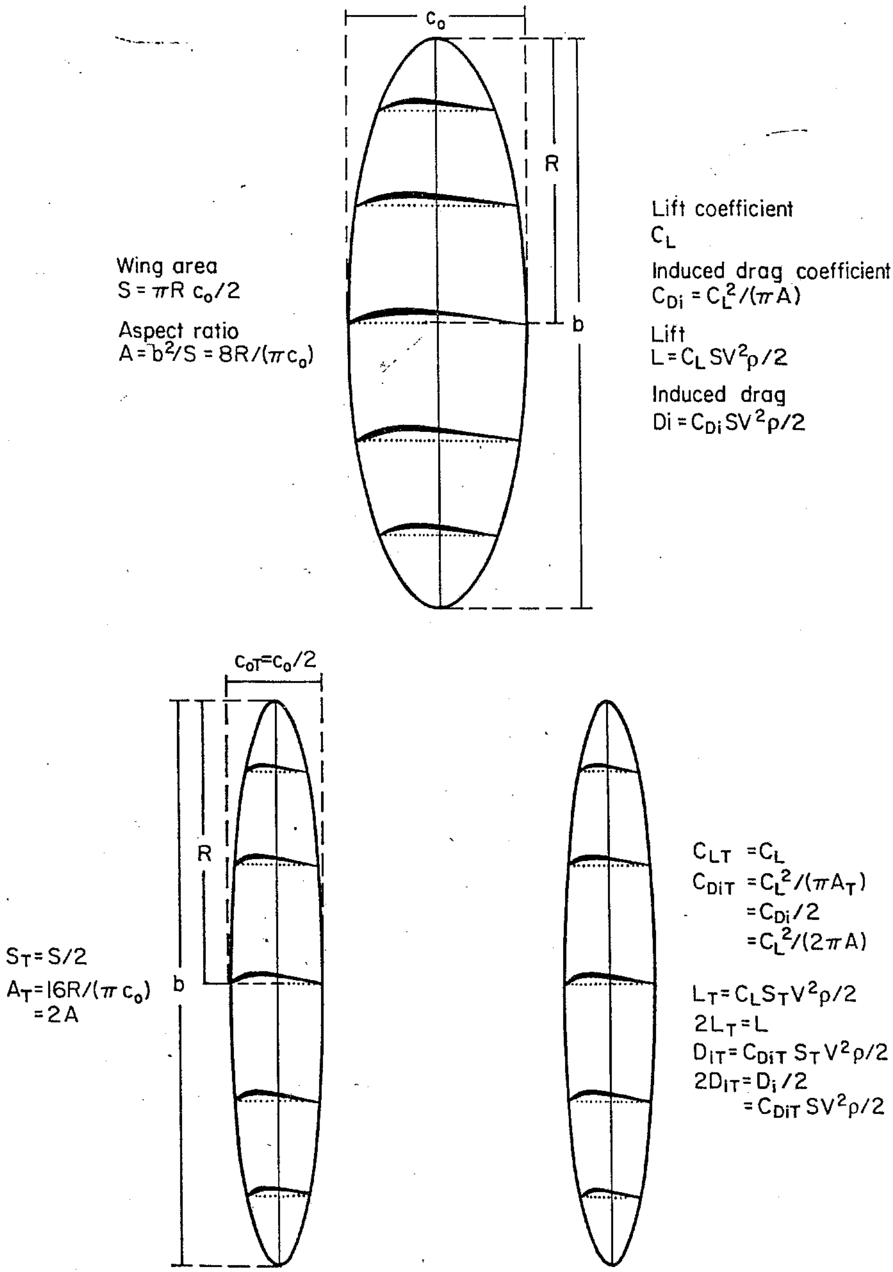

FIG. 4. Induced drag in tandem wings (see text).

original wing. Angle of incidence and air speed will remain unchanged as well. If one assumes that there is no mutual interaction between the tandem wings the total lift produced by them will be equal to that of the original undivided wing, but the total induced drag of the system will be lowered by half. However, the tandem wings will actually affect each other. The front wing flies in the upwash of the rear wing, while the rear wing is affected by the downwash of the front wing. The effective angle of incidence and, consequently, lift and induced drag will go up in the front wing but decline in the

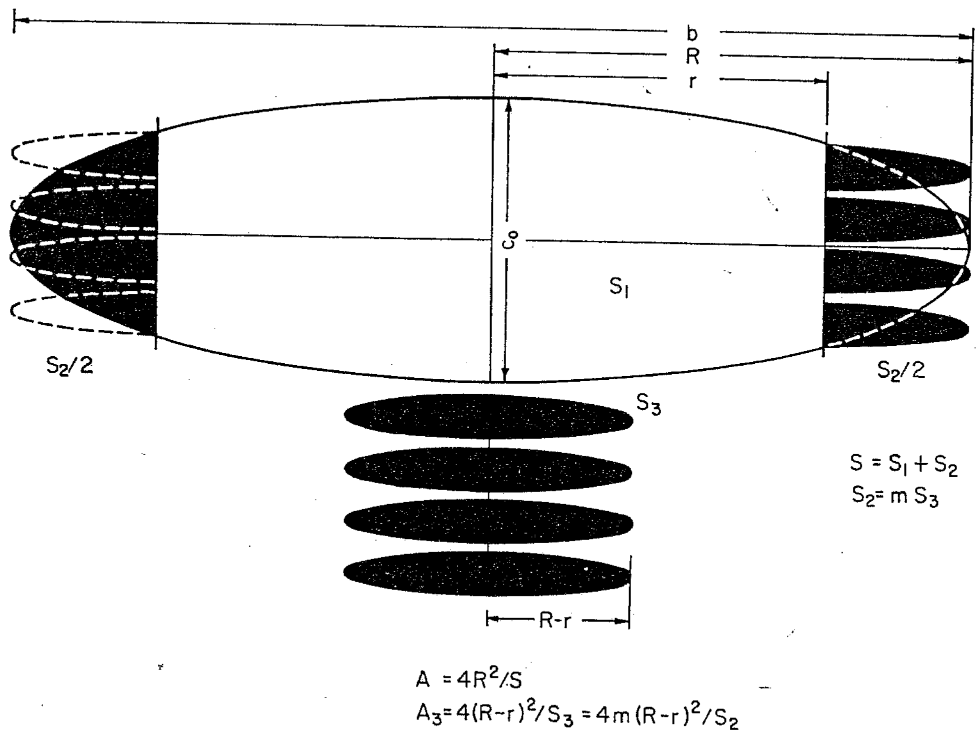

FIG. 5. Geometric foundations for change of drag in response to splitting the wing ends into tandem wings (see text and appendix).

rear. Total lift and total induced drag, however, remain equal to their ideal values. Nothing will be changed, either, if the rear wing is set slightly above or below its original position. Only the distribution of lift between the component wings will vary, and at best will have the effect that the lift is equal in each of them. This principle can be applied to more than two tandem wings so that, theoretically, by subdividing a given wing into *m* equal wings of unchanged span and profile geometry the total induced drag of the wing system can be reduced to the *m*th part of the value which the wing would experience in its original undivided condition.

This phenomenon should also be effective on a wing in which the outer parts consist of small wings arranged one behind the other. This can be shown more conveniently by calculation on the basis of a simplified model rather than by using the actual bird's wing with all its peculiarities. Any geometric or aerodynamic twisting or sweep-back of the small wings will not be considered. Again, the original wing is assumed to be untwisted and of elliptic outline (Fig. 5). The outer part of the wing on either side will be cut off parallel to the plane of symmetry (c_0) at distance r. Its area $S_2/2$ is replaced by m semiellipses, equal in size and with major semiaxis $R - r$.

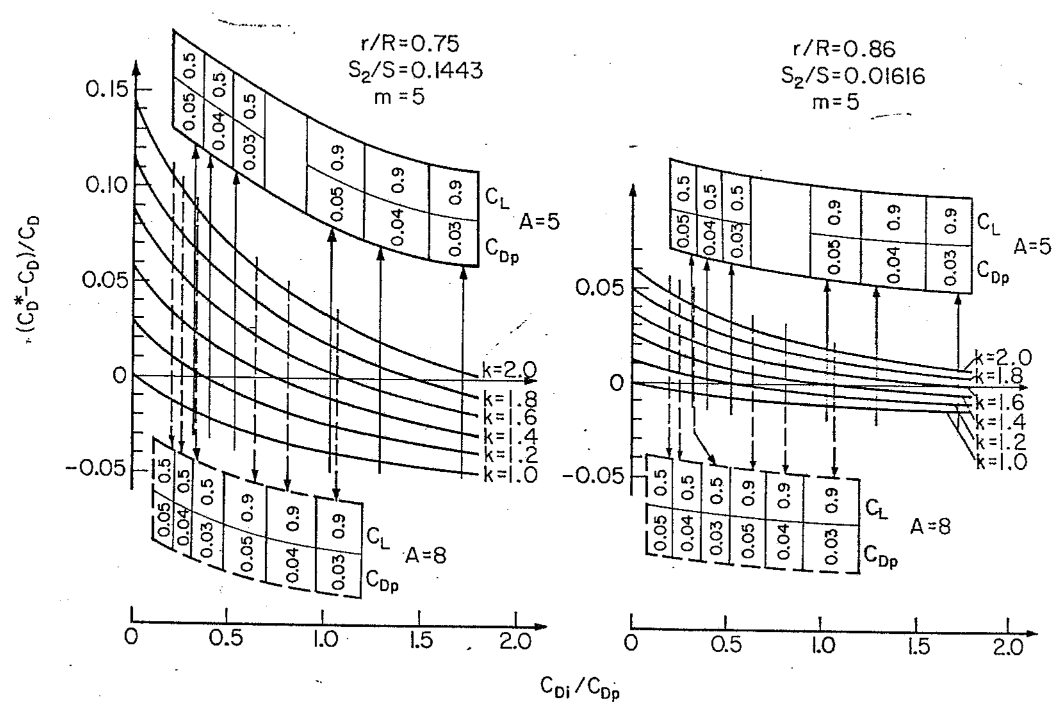

FIG. 6. Change of total drag in response to splitting the wing ends into $m = 5$ tandem wings; left hand for $r/R = 0{\cdot}75$, $S_2/S = 0{\cdot}1443$; right hand for $r/R = 0{\cdot}86$, $S_2/S = 0{\cdot}0616$; see text.

These semiellipses are assumed to be united to give elliptic wings arranged one behind the other and the coefficient of induced drag is calculated for such small wings. The coefficient of induced drag C_{Di} in the non-split part S_1 is assumed to be equal to that of the original wing. The coefficient of induced drag in the modified wing becomes

$$C^*_{Di} = C_{Di}(1 - S_2/S) + C_{Di_3}S_2/S$$

with C_{Di_3} being the coefficient of one of the small elliptic wings. The further assumption is made that the lift coefficient C_L is equal at all points of the wing span, both in the original condition and after modification, and that the coefficients of profile drag are independent of lift coefficient. The profile drag coefficient is C_{Dp} for the original wing, constant over span $2R$ and over the inner part of the wing after modification. The profile drag coefficient of one of the small wings is C_{Dp_3}, constant over its span $2(R - r)$. The total drag coefficient is $C_D = C_{Di} + C_{Dp}$ in the original and

$$C_D^* = (C_{Di} + C_{Dp})(1 - S_2/S) + (C_{Di_3} + C_{Dp_3})S_2/S$$

in the modified wing. The calculation is given in the appendix.

The variation of total drag of the modified wing compared with that of the original wing is given by the expression $(C_D^* - C_D)/C_D$. In the graphs of Fig. 6 this ratio is plotted against the ratio of induced drag to profile drag in the original wing C_{Di}/C_{Dp}. The parameters are the aspect ratio (A), the lift coefficient (C_L), the profile drag coefficient of the original wing, equal to that of the non-split inner part of the wing (C_{Dp}), and the ratio of profile drag coefficient of a tandem wing to that of the original wing ($k = C_{Dp_3}/C_{Dp}$). The values of $x = r/R$ used in the calculations were 0·75 and 0·86 respectively.

Drag reduction in the modified wing increases with increasing number of tandem wings, with an increase in their fractional area, with increasing lift coefficient, and with decreasing aspect ratio of the whole wing. Growth of profile drag in the tandem wings relative to that in the mid-wing is accompanied by rapid decline in drag reduction and even by growth of drag in the modified wing, i.e. by a deterioration of gliding performance. In addition, it should be borne in mind that reduction of lift in the small wings may not only lower drag savings but may even cause drag rise, since the span-constant lift coefficient applicable to the original wing would be smaller.

The growth of profile drag in the tandem wings is a phenomenon which depends on the size of the entire wing. Every wing profile has its own characteristic critical value of the Reynolds number. The ratio of lift to profile drag is relatively poor below the critical value, on account of separation of the laminar boundary layer, which tends to occur on the suction side. The same ratio is improved above the critical value, since the boundary layer on the suction side will be turbulent (cf. Schmitz [10, 11]). The Reynolds number is given by $\mathrm{Re} = Vc/\nu$, where V is the air speed, c the chord length, and ν the kinematic viscosity of the flowing medium. Since the chord lengths of the tandem wings are much smaller than those in the unsplit part of the wing, the latter may be above the critical value of Re and the former below, at any given speed. The considerable difference in the two values of Re is shown in Fig. 7, with particular reference to the value $\mathrm{Re} = 10^4$.

This is the situation in greater detail: the wing is assumed to have a profile which is insensitive to changes of Reynolds number over a wide range (a plane or cambered plate with sharp leading edge). Then, according to Schmitz,[11] development of a turbulent boundary layer on the suction side should be expected for $\mathrm{Re} > 10^4$. In this region variation of the Reynolds number will be accompanied by little variation of C_L/C_D. But for Re < 10^4 a growth of profile drag in such wing sections should be assumed to take place, along with a remarkable decline in lift (Fig. 8). If one further assumes that the bird's wing has such profiles—the sharp leading edge of the thicker inner segment of the wing and the surface roughness of the feather structures

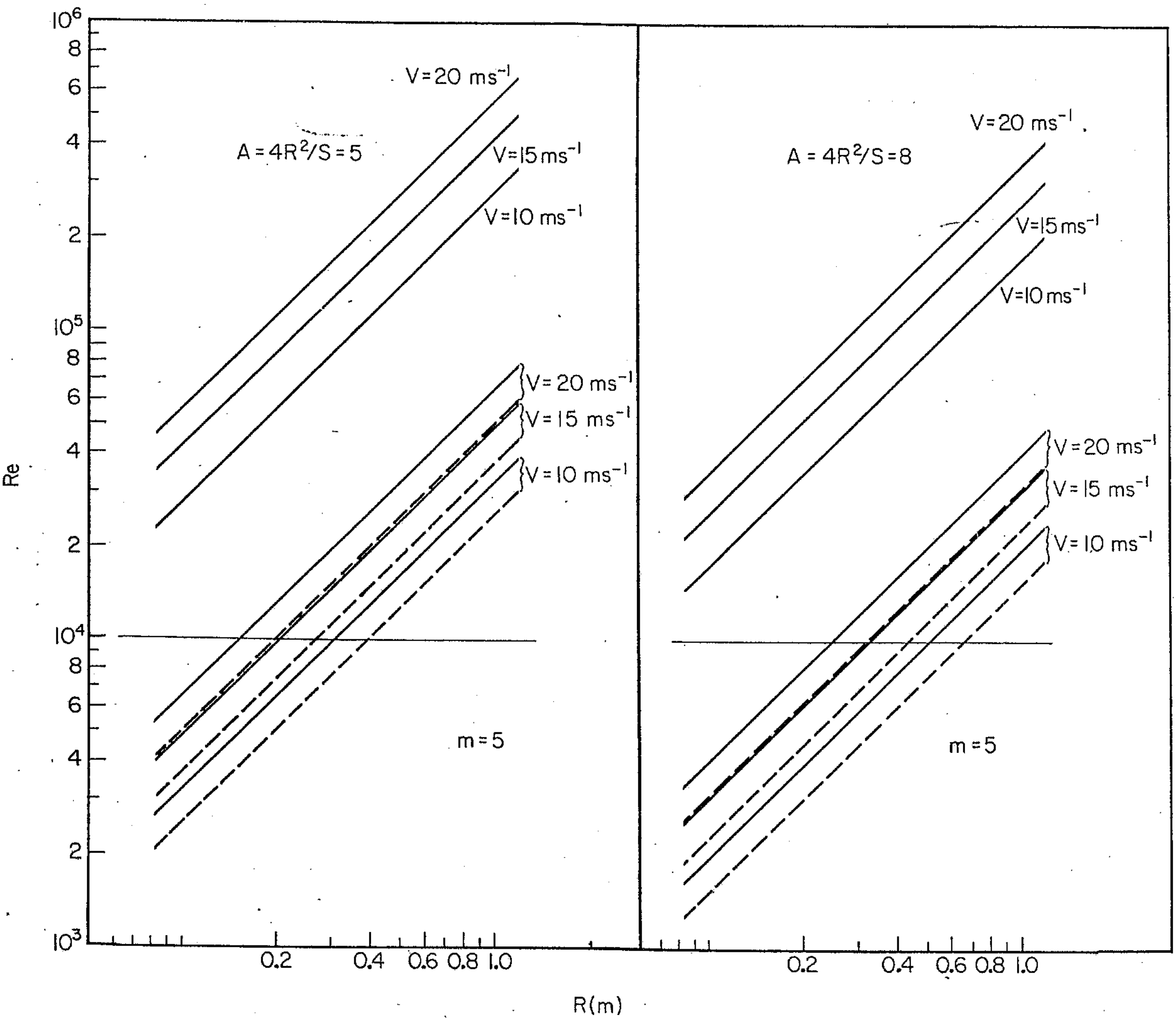

FIG. 7. Dependence on wing size of Reynolds number for mean chord lengths of original wing (top) and tandem wings of the split outer parts of the modified wing (bottom); full lines for $r/R = 0{\cdot}75$, dotted lines for $r/R = 0{\cdot}86$.

being interpreted as turbulence generators (cf. Nachtigall and Wieser,[5] Oehme[6, 7])—then calculation of Reynolds numbers for the chord length at $R/2$ and for an average chord length in the middle of all the separated primaries of the bird species under investigation, for one and the same speed, gives fairly good agreement with the theoretical model (Fig. 9). Hence, for smaller birds, up to thrush size, the lift–drag ratio will not be improved by means of separated primaries. On the contrary a deterioration of gliding performance is very likely to occur. The potential benefit of separated primaries is questionable even in larger species for low flight speeds.

This conclusion really applies only to the model, in other words, to an approximation of gliding or soaring flight of the bird in general. In fact, none of the species will reach the upper limit of 20 m s^{-1}, and some of them will do no steady-state gliding or soaring at all, or at least not with wings fully stretched and hence outer primaries separated. Yet, for the time being, let us

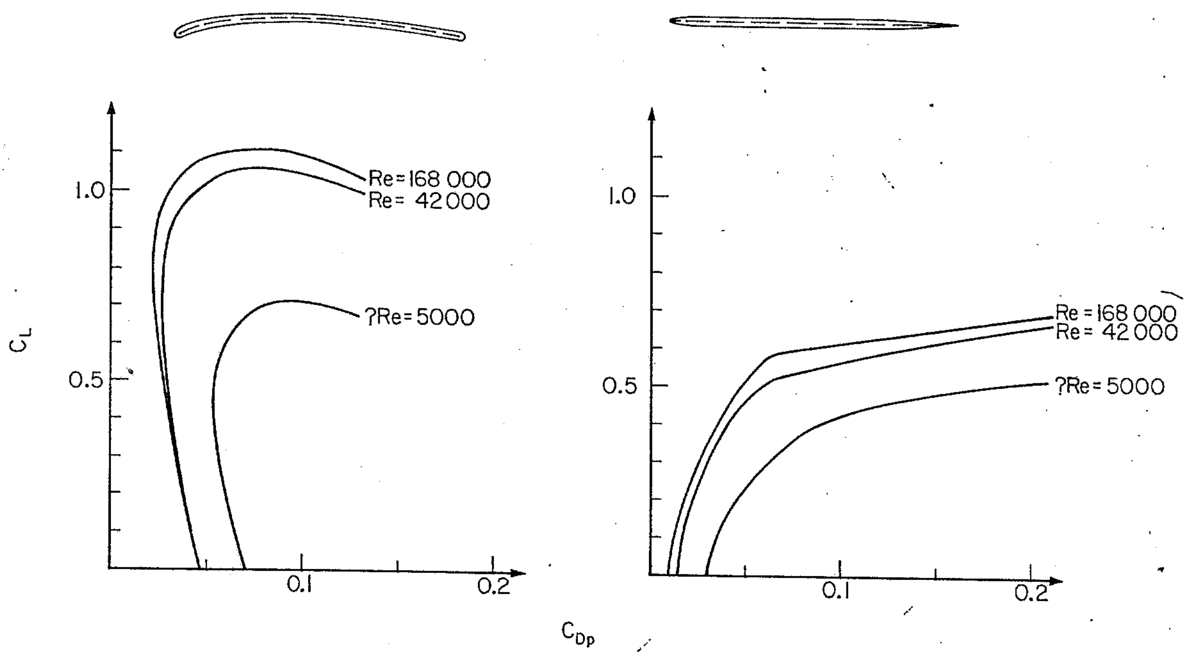

FIG. 8. Polar curves for thin wing sections with different Reynolds numbers, according to Schmitz;[11] a probable curve for Re ≈ 5000 is added.

still insist on this assumption in order to touch upon two more problems, profile design and the fine structure of separated primaries. The transverse sections of primaries are not homogeneous, but three major types may be differentiated (Fig. 10): the blackbird type (including redstart, house sparrow, magpie, jackdaw, rook, hooded crow) with thin, cambered plates (maximum camber between three and seven per cent of chord length); the pigeon type (domestic pigeon, collared turtle-dove) with profiles thin and almost symmetrical, somewhat comparable to flat plates; the mallard type (including starling, kestrel, black-headed gull) with a flat plate in the foremost large primary, but cambered plates in the others. A fairly large and more or less constant lift coefficient up to the wing tip, the prerequisite for a positive tandem effect, can be expected for the first type, and perhaps for the third as

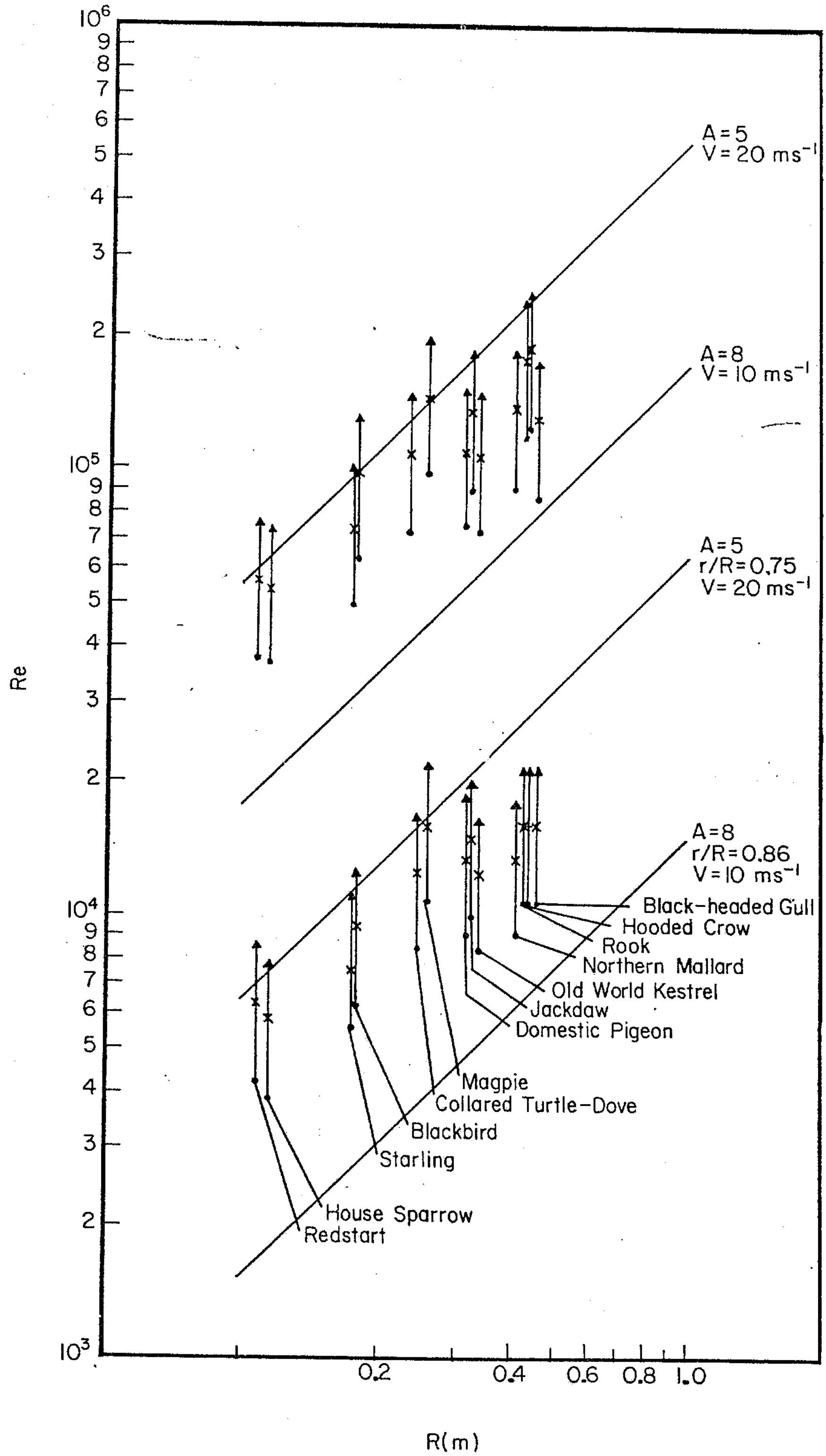

FIG. 9. Reynolds numbers of bird wings for chord length at $R/2$ (top) and average vane width at mid-point of separated primaries (bottom) plotted against wing length R for $V = 10\ \mathrm{m\,s^{-1}}$ (●), $V = 15\ \mathrm{m\,s^{-1}}$ (×), $V = 20\ \mathrm{m\,s^{-1}}$ (▲); also plotted for comparison are maximum and minimum values of model example, cf. Fig. 7.

well. But a positive tandem effect (improvement of gliding performance) should be expected only for birds of the size of jackdaw or larger, and it should not occur to any great extent unless the distal segment of the wing is deeply split. As to the species quoted above, it should be justified for magpie, jackdaw, rook, and hooded crow, and it probably applies to many larger birds, such as eagles, vultures, buzzards, harriers, storks, herons, and cranes, although the profiles of their primaries are unknown. The pigeon type seems to represent a different trend. Strong lift would cause high profile drag in the

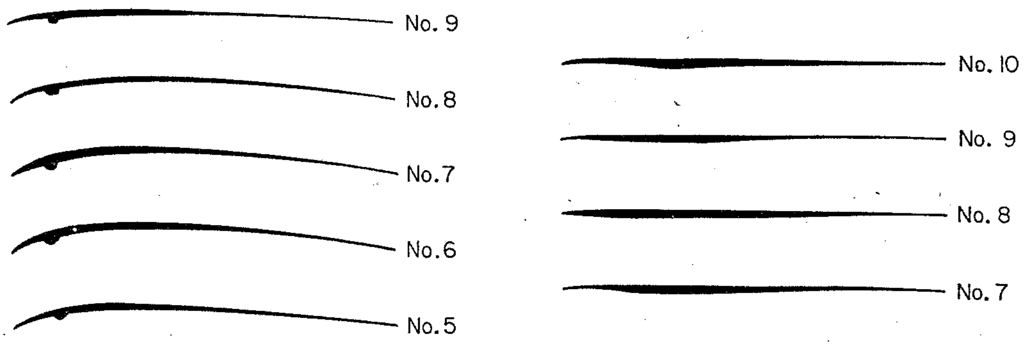

FIG. 10. Adjusted outlines of transverse sections at mid-point of separated primaries from *Turdus merula* (left hand) and *Columba livia* (right hand).

split part of the wing, and render impossible any reduction of total drag. If, on the other hand, the action of the separated primaries took place with smaller angles of incidence and hence lift coefficients below those in the inner part of the wing, the profile drag in the primaries would be lower. However, no reduction of total drag would be possible either, as we saw in the context of the model example. Separated primaries of such design probably have no significant tandem effect, especially as in their case the distal segment of the wing is obviously less split.

While at first glance a classification of structural peculiarities in the distal segment of the wing appears to be feasible, through their influence on drag variation, an additional uncertainty unfortunately arises. The transverse sections of the primaries so far described are idealised outlines. The real appearance of such a "profile" may be seen in Fig. 11. Surface roughness generated by the barbs is up to one per cent of the chord length on the suction side and up to four per cent on the pressure side. The question of whether such a structure still has the lift-drag characteristics of idealised profiles with similar contour is unanswered. It remains unelucidated even if smaller Reynolds numbers are considered, which would apply to such "wings" and for which turbulence generators, on principle, would be favourable. Therefore, further studies into the drag problem of the bird's wing are necessary to complement this theoretical concept or to propose some modification of it.

Finally we have to consider the efficacy of the tandem effect in powered flight. While in unaccelerated horizontal flight the flow acting upon the wing can be assumed to be steady (von Holst and Küchemann,[2] Oehme and Kitzler[8]) and the wing in its downstroke can be treated like a propeller with a high advance ratio (cf. Nachtigall,[3] Oehme and Kitzler[9]). The direction of the aerodynamic force generated will increasingly tilt forward, from wing

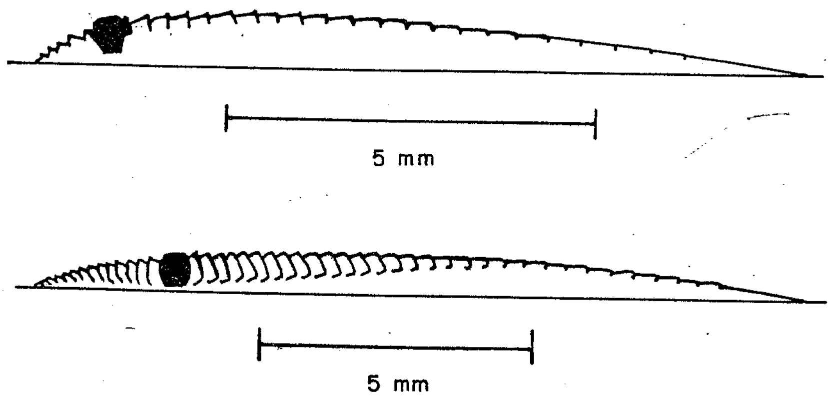

FIG. 11. Microstructure of transverse sections of separated primaries, primary No. 7 of *Turdus merula* (top) and primary No. 9 of *Anas platyrhynchos* (bottom).

base to wing tip, and the effective air-speed will also grow relative to flight speed. An elliptic lift distribution, such as that used in the model, can no longer be expected. Nevertheless, it is plausible that if drag in the outer segment of the wing goes down the downstroke will give more forward thrust. The threshold beyond which drag reduction may be expected will not, even in such a case, be surpassed by smaller birds; the greatest possible value in the effective air speed in the area of the separated primaries being $20 \mathrm{m s^{-1}}$. The thrust achieved in the downstroke, however, can actually be improved in a larger bird, such as a crow, and in this case definition of separated primaries as "forward-thrust-feathers" (Stresemann[13]) seems to be justified. The principle that separated primaries depend on size for their drag-reducing action, as expounded by the simplified model of a rigid wing, is valid for normal powered flight as well.

CONCLUSIONS

By analysis of the flight performance of separated primaries, a set of new questions is established which cannot be answered in this paper, but the major issues relating to them should be mentioned. A completely closed wing tip, as recorded in swifts and hummingbirds, is not displayed by the stretched wing of most bird species. More or less strongly pronounced separation of the outer primaries is common. The aerodynamic implications elucidated in this paper do not support an interpretation of this morphological structure as a device to reduce wing drag. Such a drag-reducing function *may* occur, and if it does it depends on a minimum size of the bird and on the shape of its primaries. The structural peculiarity of "separated primaries" is more likely to be explained by other functional relations. Partial answers may be found (i) in the context of asking whether a closed wing tip is consistent with the elastic stress experienced by it in the downstroke during powered flight, (ii) in the bird's ability to use its wings in a great variety of ways (folding and unfolding, use as an inversed blown wing system in upstroke while hovering, deceleration, and acceleration), and (iii) in the restriction of the basic design in the bird's forelimb to certain structural parts. However, the most likely explanation is that suggested by Kokshaysky above, to the effect that (iv) separated primaries enable the distal part of the wing, and indeed the individual feathers, to be twisted far enough to increase the angle of incidence substantially without stalling, thereby increasing the total lift coefficient. They may also be used to *decrease* the effective angle of attack at the wing-tip when the main wing is almost stalling, in order to prevent the stall (Nachtigall, discussion).

APPENDIX

CALCULATION OF DRAG OF A WING WITH OUTER PARTS SPLIT INTO TANDEM WINGS

(a) Geometry

Wing with elliptic outline, span $b = 2R$, aspect ratio $A = b^2/S = 4R^2/S$ with wing area S. Major semiaxis of ellipse R, minor semiaxis $c_0/2$, chord length in the plane of symmetry c_0. $A = 8R/(\pi c_0)$ and $c_0 = 8R/(\pi A)$, because $S = \pi R c_0/2$ and $S = 4R^2/A$. Wing ends are cut off parallel to c_0 at distance r and replaced by m semiellipses, equal in size and with their major semiaxis being $R - r$. Area of the two cut wing ends S_2, remaining area of original wing S_1, area of one of the small ellipses composed of both halves S_3; $S_2 = mS_3$. Chord length at r is

$$c_r = c_0\sqrt{(1 - x^2)} = 8R\sqrt{(1 - x^2)}/(\pi A)$$

with $x = r/R$.

Area of segment of ellipse

$$S_2/2 = 4R^2 \arccos x/(\pi A) - 4R^2 x\sqrt{(1 - x^2)}/(\pi A).$$

Therefore,

$$S_2 = 8R^2[\arccos x - x\sqrt{(1 - x^2)}]/(\pi A)$$

and

$$y = S_2/S = 2[\arccos x - x\sqrt{(1 - x^2)}]/\pi.$$

Area of one small ellipse

$$S_3 = S_2/m = yS/m = 4yR^2/(mA),$$

its aspect ratio

$$A_3 = 4(R - r)^2/S_3 = 4R^2(1 - x)^2/S_3 = mA(1 - x)^2/y.$$

Mean chord length of original wing $\bar{c} = S/2R = 2R/A$, mean chord length of small elliptic wing $\bar{c}_3 = S_3/[2R(1 - x)] = \bar{c}y/[m(1 - x)]$.

(b) Drag Coefficients

Total lift equal in original wing (S) and modified wing ($S_1 + mS_3$). Elliptic lift distribution is assumed in the original (untwisted) wing. Therefore, C_L is constant from wing tip to wing tip. Further C_L has to be of equal value in all wing sections of S_1 and S_3. Induced drag coefficient in the inner, non-split part of the modified wing is assumed equal to that in the original wing, a condition not completely satisfied in reality.

Values of induced drag:

in the original wing

$$C_{Di} = C_L^2/(\pi A),$$

in the small elliptic wing

$$C_{Di3} = C_L^2/(\pi A_3) = C_{Di}y/[m(1 - x)^2],$$

in the wing after modification

$$C_{Di}^* = C_{Di}(1 - y) + yC_{Di3} = C_{Di}\{1 - y + y^2/[m(1 - x)^2]\}.$$

Change of induced drag

$$(C_{Di}^* - C_{Di})/C_{Di} = y\{y/[m(1 - x)^2]\}.$$

Coefficient of profile drag in the original wing, constant over span $2R$, and in all sections of inner part of wing S_1 is C_{Dp}, while coefficient of profile drag in a tandem wing S_3, constant over span $2(R - r)$, is C_{Dp3}.

Drag coefficient in the original wing $C_D = D_{Di} + C_{Dp}$, in the modified wing

$$C_D^* = C_{Di}^* + (1 - y)\, C_{Dp} + yC_{Dp3}.$$

Given $k = C_{Dp_3}/C_{Dp}$, then

$$\begin{aligned} C_D^* &= C_{Di}^* + (1 - y)\, C_{Dp} + ykC_{Dp} \\ &= C_{Di}\{1 - y + y^2/[m(1 - x)^2]\} + C_{Dp}(1 - y + yk). \end{aligned}$$

Change in total drag becomes

$$\begin{aligned} (C_D^* - C_D)/C_D = {} & C_{Di}\, y\{y/[m(1 - x)^2] - 1\}/(C_{Di} + C_{Dp}) \\ & + C_{Dp}\, y(k - 1)/(C_{Di} + C_{Dp}). \end{aligned}$$

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