

CONTROL OF GLIDING ANGLE IN RÜPPELL'S GRIFFON VULTURE *GYP S RÜPPELLII*

By C. J. PENNYCUICK

Department of Zoology, University of Nairobi

(Received 2 November 1970)

INTRODUCTION

A bird or sailplane in a straight, unaccelerated glide descends at an angle θ below the horizontal, where

$$\theta = \cot^{-1} \left(\frac{L}{D} \right). \quad (1)$$

L/D , the lift: drag ratio, thus directly determines the gliding angle, and is often referred to as the 'glide ratio'. The refinements of glider design, and the adaptations of soaring birds, are largely directed towards maximizing this ratio, so as to achieve as flat a gliding angle as possible, but there are occasions when the descent path of any bird or glider has to be adjusted to some steeper angle than the flattest of which it is capable. All sailplanes are provided either with tail parachutes or (more commonly) with adjustable 'airbrakes' whose function is to generate drag without extra lift. For example, the airbrakes of the Ka-6 CR sailplane, which is typical in this respect, allow its glide ratio to be adjusted continuously from 29:1 to 7:1 without change of speed (Merklein, 1963), a facility which is indispensable when landing the sailplane accurately on a chosen spot. Even steeper gliding angles can be obtained by increasing speed with the brakes open.

Gliding birds have several methods of steepening their gliding angles, of which the simplest is to lower their feet below the body, thus producing a controllable amount of extra drag, in a manner analogous to the action of a glider's airbrakes. The use of the feet for gliding angle control is especially effective and conspicuous in water birds which have webbed feet (Pennyquick & Webbe, 1959; Pennyquick, 1960), but it has also been found that the feet of the pigeon *Columba livia* are highly effective as airbrakes, and are constantly used to make small adjustments by pigeons trained to fly in a wind tunnel (Pennyquick, 1968).

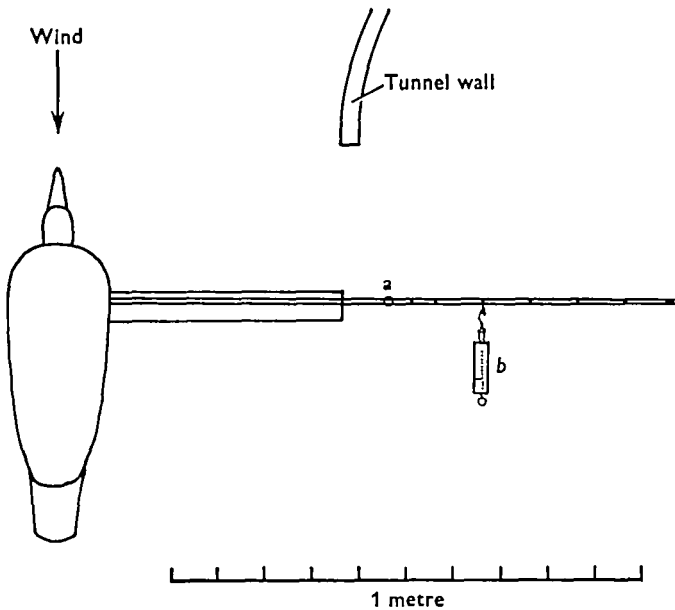
The purpose of the present paper is to assess the extent to which a vulture can control its gliding angle by the use of its feet, and also to consider some other ways in which the effect of the feet might be augmented.

MATERIAL AND METHOD

The measurements described below were made on a specimen of Rüppell's griffon vulture *Gyps rüppellii*, whose mass with the crop empty was 6.9 kg when shot. The wings were removed by disarticulating the shoulder joints. The body was frozen and mounted on a steel rod terminating in two spikes which were inserted transversely to

the body axis opposite the right shoulder joint, near the centre of gravity. The whole was supported on a horizontal brass tube, which held the body in the working section of a wind tunnel 1 m in diameter. That portion of the support tube which was exposed to the airstream was enclosed in a sheet-metal fairing, which was faired into the body with Plasticine.

The support tube was pivoted between a pair of ballraces mounted outside the wind tunnel, and the drag moment exerted by the wind on the body and its support was measured with a spring balance as shown in Text-fig. 1. After correcting for the zero error of the balance and the drag moment of the support, the drag of the body was obtained by dividing the measured drag moment by the distance between the pivot and the centre-line of the body.



Text-fig. 1. View from above of the frozen vulture body supported in the working section of the (open jet) wind tunnel. The support bar is pivoted at *a*, and the total drag moment is measured with the spring balance *b*, which can be attached to the bar at several alternative positions.

A description of the wind tunnel is given by Pennycuick (1968).

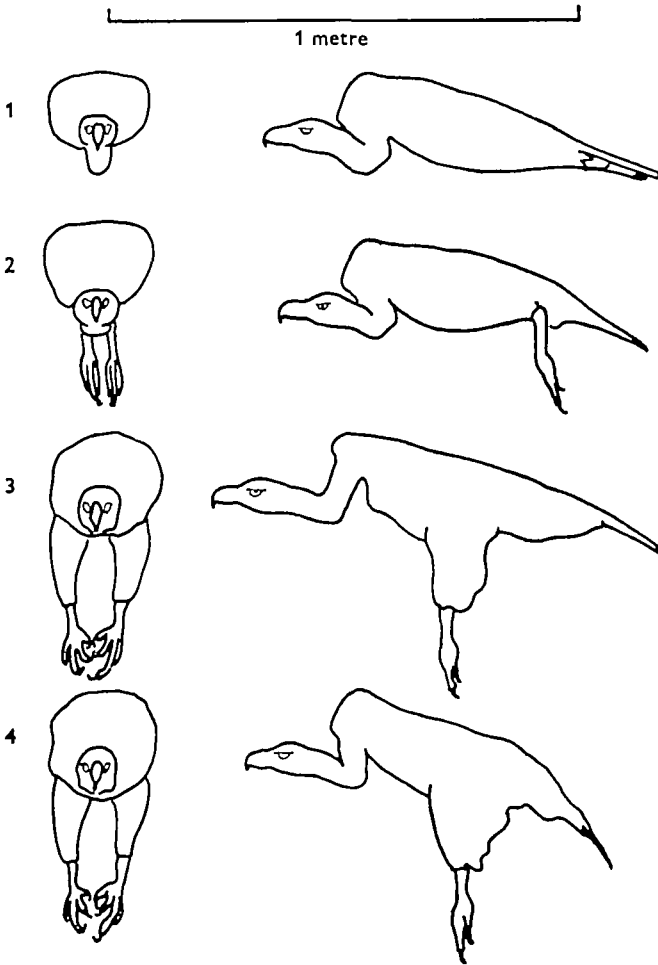
All the measurements were made at an equivalent air speed of 12.0 m/s. This speed corresponds to a lift coefficient of 1.0, and lies between the speeds for minimum sink (11 m/s) and best gliding angle (14–15 m/s) calculated by the methods indicated below. The Reynolds Number, based on the square root of the greatest cross-sectional area of the body, was about 140000.

RESULTS

Drag measurements were made with the body frozen in four different positions. After each test the body was photographed, together with a metre rule, from various angles, and tracings of the photographs, all at the same scale, are shown in Text-fig. 2.

In position 1 the feet were raised with the toes furred horizontally beneath the tail, and the neck was also fully retracted. The positions chosen were judged from photo-

graphs and observations of free-flying vultures to be characteristic of normal cruising flight with minimum drag. The measured drag was 1.13 N at an equivalent airspeed of 12.0 m/s, and the maximum cross-sectional area of the body, measured from the photographs, was 0.0300 m². The drag coefficient was thus 0.43, the same value as was obtained for the pigeon *Columba livia* by Pennycuick (1968).



Text-fig. 2. The four positions in which the body was set for the drag measurements.

The attitudes of positions 2 and 3 were selected after spending some 20 h watching vultures soaring at the breeding colony on the Gol Escarpment, Tanzania, and studying a large number of photographs taken there. The positions chosen were considered to be typical of vultures in moderate and steep descents respectively.

In position 2 the feet were lowered from the tarso-metatarsal joints, and the toes partially spread, exposing a frontal area about one-third that of the body. This resulted in a drag increment of 0.75 N; if it is assumed that the drag of the feet and that of the body were additive, then the drag coefficient of the feet would be 0.87.

When the legs were fully lowered and the toes spread further (position 3), the extra

frontal area of the legs and feet was about 86% that of the body, but the drag increment was 2.46 N, i.e. over twice the drag of the body with the feet raised. On this basis the drag coefficient of the legs and feet was 1.08, which may be compared with values of 1.10–1.25 for the fully spread isolated foot of the pigeon (PennyCUICK, 1968).

Position 4 was the same as position 3, except that the tail was depressed through about 38°, though not spread. This resulted in a further drag increment of 1.41 N, presumably due to separation of the flow over the upper surface of the body.

The results are summarized in Table 1.

Table 1. Drag measurements for the four body positions shown in Text-fig. 2

Body position	Total drag (N) at 12.0 m/s	Increment due to feet (N)	Frontal area of feet (m ²)	Drag coefficient of feet
1	1.13	—	—	—
2	1.88	0.75	9.8×10^{-3}	0.89
3	3.59	2.46	2.59×10^{-2}	1.08
4	5.00	3.87	2.56×10^{-2}	—

DISCUSSION

In the preceding paper (PennyCUICK, 1971) the straight-flight glide polar of the smaller, but otherwise similar, white-backed vulture *Gyps africanus* was assumed to obey the relationship

$$V_z = \frac{\beta}{V} + \gamma V^3, \quad (1)$$

where V_z is the equivalent sinking speed and V the equivalent forward speed. The physical interpretations of the constants β and γ are

$$\beta = \frac{2kW}{\pi A \rho_0 S}, \quad (2)$$

$$\gamma = \frac{C_{D0} \rho_0 S}{2W}, \quad (3)$$

where W is the bird's weight, A is its aspect ratio, S is its wing area, k is the span efficiency factor, ρ_0 is the air density at sea level in the standard atmosphere, and C_{D0} is the drag coefficient at zero lift.

Average measurements used in the performance estimates were

$$W = 74.3 \text{ N},$$

$$S = 0.830 \text{ m}^2,$$

$$A = 7.0,$$

$$\rho_0 = 1.22 \text{ kg m}^{-3}.$$

The average weight and wing area were derived from a sample of nineteen birds collected by Mr D. C. Houston, to whom I am indebted for the information, while the aspect ratio was based on a detailed planform tracing of one specimen made by the writer.

In estimating the glide polar for the 'clean' vulture (with feet retracted and wings

fully spread), k is taken to be 1 and C_{D0} to be 0.0232, as in the preceding paper. The resulting values of β and γ are listed in the first line of Table 2 in the columns headed 'wings extended', and when substituted in equation (1) give the equation of the basic polar. This is plotted as the uppermost curve in Text-fig. 3 and represents an estimate of the minimum sinking speeds of which the vulture is capable at low to medium forward speeds.

Table 2. Constants for the glide polar with wings fully spread, and with span and area reduced to two-thirds of their maxima

Body position	Wings extended $\beta = 6.67 \text{ m}^2 \text{ s}^{-2}$		Wings flexed $\beta = 15.1 \text{ m}^2 \text{ s}^{-2}$	
	C_{D0}	$\gamma \text{ (m}^{-2} \text{ s}^2)$	C_{D0}	$\gamma \text{ (m}^{-2} \text{ s}^2)$
1	0.0226	1.54×10^{-4}	0.0303	1.38×10^{-4}
2	0.0329	2.24×10^{-4}	0.0458	2.08×10^{-4}
3	0.0563	3.84×10^{-4}	0.0809	3.67×10^{-4}
4	0.0757	5.16×10^{-4}	0.110	5.00×10^{-4}

The effect of lowering the feet is to modify the polar by increasing C_{D0} and hence γ , so increasing the sinking speed at all forward speeds, but more at high than at low speeds. Other expedients are available to the bird which increase β , the effect of which is to increase the sinking speed more at low than at high speeds. The effect of exercising these various options singly or in combination will now be considered in terms of their effect on the glide polar.

Effect of feet alone

The value of 0.0232 for C_{D0} , which was derived from the experimental measurements on the white-backed vulture, is made up of a component due to the body C_{D0B} , and one due to the wing C_{D0W} :

$$C_{D0} = C_{D0B} + C_{D0W}. \quad (4)$$

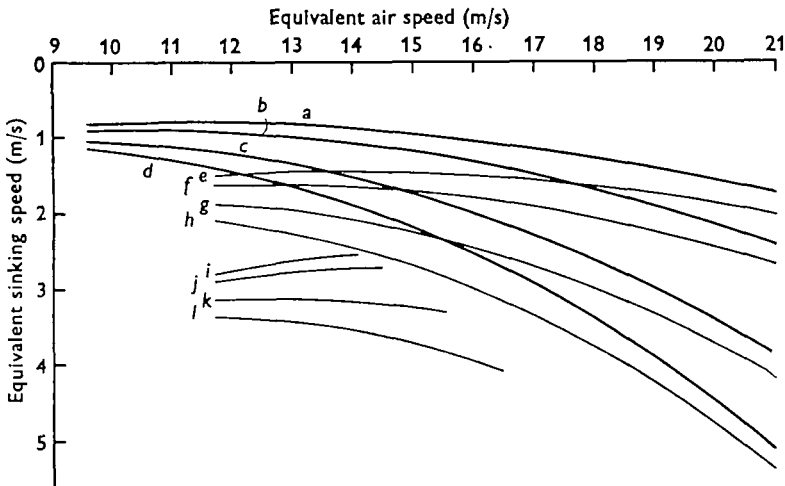
C_{D0B} is estimated from the drag measurements given here as 0.0161, and C_{D0W} , by subtraction, is 0.0071.

It will be assumed first of all that the body positions shown in Text-fig. 2 are successively adopted, while the wings are held at their full span. The only effect of this should be to increase C_{D0B} . After adding C_{D0W} , the resulting values of C_{D0} and of γ are listed in Table 2 for the different body positions, in the columns headed 'wings extended'. The polars so calculated for the four positions of Text-fig. 2 are marked *a-d* in Text-fig. 3. By lowering the feet fully the vulture should be able to reduce its best glide ratio from 15.5 to 10.3 whilst depressing the tail as well should further reduce it to 8.8. Actually the vultures do not seem to use their tails in this way, but on the other hand it was noticed that the feathers on the back usually lift and shake about when the feet are lowered, suggesting that lowering the feet causes the air flow over the back to separate. If this is so, curve *d* may be a more accurate estimate of the effect of fully lowering the feet than curve *c*.

Combined effect of lowering feet and reducing wing span

It will now be assumed that in addition to lowering the feet, the vulture retracts its wings to two-thirds of their full span, and that this also has the effect of reducing the wing area to two-thirds of its maximum value. This increases the wing loading by

a factor of 1.5, and reduces the aspect ratio by a factor of two-thirds, causing β to increase by a factor of 1.5², equation (2). C_{D0B} is increased because the same body drag is now referred to a smaller wing area, but since this is only one component of C_{D0} , (equation 4), and the other (C_{D0W}) remains constant, C_{D0} is not increased by the full amount of the increase in wing loading. The increase in C_{D0} is thus more than offset by the reduction in S (equation 3), so that the net effect on γ is to reduce it slightly. The increase in β means that sinking speeds at low forward speeds are increased, but the reduction of γ means that at very high speeds the sinking speed would be less than with the wings fully extended.



Text-fig. 3. Polar curves calculated as explained in the text. *a-d*: the body in positions 1-4 respectively (see Text-fig. 2), and the wings fully extended. *e-h*: The same, with both wing span and wing area reduced to two-thirds of their full values. *i-l*: The same as *e-h*, but with doubled induced drag.

The new values of the constants are listed under 'wings flexed' in Table 2. The new set of polars (*e-h* in Text-fig. 3) starts off below the original set (*a-d*), but would eventually cross over them if the diagram were extended further to the right. There is now a well-marked 'worst glide ratio', ranging from 5.5 to 7.7, at the minimum speed, where the airbrake effect is most pronounced. If the maximum lift coefficient is assumed to remain at 1.6, however, the minimum speed will be increased from 9.6 to 11.7 m/s because of the increased wing loading.

Variation of spanwise lift distribution

Many birds, when descending in steep glides, are able to decrease their wing camber over the proximal part of the wing by allowing the secondary feathers to lift up, so transferring a bigger proportion of the total lift to the primaries. The airbrakes or spoilers fitted to many gliders have a similar effect, and the use of such a mechanism as an airbrake in vultures was postulated by Hankin (1923).

Such a redistribution of lift on the spanwise direction produces an increase of induced drag, which can be represented by increasing k . To see the nature of the effect, the previous set of curves was recalculated with $k \Rightarrow 2$. This doubles β to 30.2, whilst leaving the four values of γ listed under 'wings flexed' in Table 2 unchanged. The

Low-speed ends of the four resulting curves are plotted as *i-l* in Text-fig. 3. The greatest effect is again at the minimum speed, where the 'worst glide ratios' now range from 3.4 to 4.2, whilst at high speeds these curves would approach the corresponding members of the last set, *e-h*.

Uses of different mechanisms

When the *Gyps* vultures are gathering at a kill they often hurtle across the sky making a loud rushing sound which can be heard on the ground a long way off. At such very high speeds reduction of the wing area appears to be necessary for trim but would of itself produce little if any steepening of the gliding angle. Lowering the feet, however, produces a large amount of drag at high speeds, and is a highly effective method of controlling the angle of these fast glides.

On the other hand vultures manoeuvring in slope lift around the nesting cliffs are often flying near their minimum speeds and have to make frequent adjustments of their gliding angle in order to compensate for variations in vertical air velocity. Under these circumstances the feet are only moderately effective as airbrakes, while adjustments of wing shape become highly effective, the more so as the minimum speed is approached.

I am most grateful to Mr D. C. Houston of the Serengeti Research Institute for providing the specimen used for these measurements, and to Mr C. Hillman for constructing the drag balance. My thanks are also due to Mr S. A. Ole Saibull, Conservator of the Ngorongoro Conservation Area, for permission to make observations at the Gol cliffs, and also to Mr Hillman and Prof. D. Robertshaw, who were at different times my companions on several memorable expeditions there. The transport of the wind tunnel from its former site at Bristol to Nairobi was financed by grants from the East African Wild Life Society, the Ministry of Overseas Development and the University College Nairobi (now the University of Nairobi), and I am most grateful to all of these organizations for their help.

SUMMARY

1. The drag of the frozen, wingless body of a Rüppell's griffon vulture was measured in a wind tunnel with a simple drag balance. The drag coefficient with feet and neck retracted was 0.43, based on the greatest cross-sectional area of the body.

2. The drag of the body was trebled by fully lowering the feet, and more than quadrupled when the tail was lowered as well, apparently owing to separation of the flow over the back. The drag coefficient of the legs and feet, based on their frontal area, varied from 0.89 to 1.08 in different positions.

3. At low speeds the use of the feet alone should reduce the glide ratio from about 15 to 10, but the airbrake effect becomes progressively more marked at higher speeds. At lower speeds reduction of the wing area produces a greater steepening of the gliding angle, but at the expense of increasing the minimum speed. Increase of induced drag would provide a highly effective gliding angle control at very low speeds, and it is suggested that this is achieved by raising the secondary feathers, which would alter the spanwise lift distribution by transferring a greater proportion of the lift to the primaries.

REFERENCES

- HANKIN, E. H. (1923). On the air brake used by vultures in high speed flight. *Proc. Camb. phil. Soc. biol. Sci.* **21**, 424-5.
- MERKLEIN, H. J. (1963). Bestimmung aerodynamischer Beiwerte durch Flugmessungen an 12 Segelflugzeugen mit Brems- und Landeklappen. *Flugwissenschaftliche Forschungsanstalt e.V. München*. Bericht Nr. 63.
- PENNYCUICK, C. J. (1960). Gliding flight of the fulmar petrel. *J. exp. Biol.* **37**, 330-8.
- PENNYCUICK, C. J. (1968) A wind-tunnel study of gliding flight in the pigeon *Columba livia*. *J. exp. Biol.* **49**, 509-26.
- PENNYCUICK, C. J. (1971) Gliding flight of the white-backed vulture *Gyps africanus*. *J. exp. Biol.* **55**, 13-38.
- PENNYCUICK, C. J. & WEBBE, D. (1959). Observations on the fulmar in Spitsbergen. *Br. Birds* **52**, 321-32.

EXPLANATION OF PLATES

PLATE 1

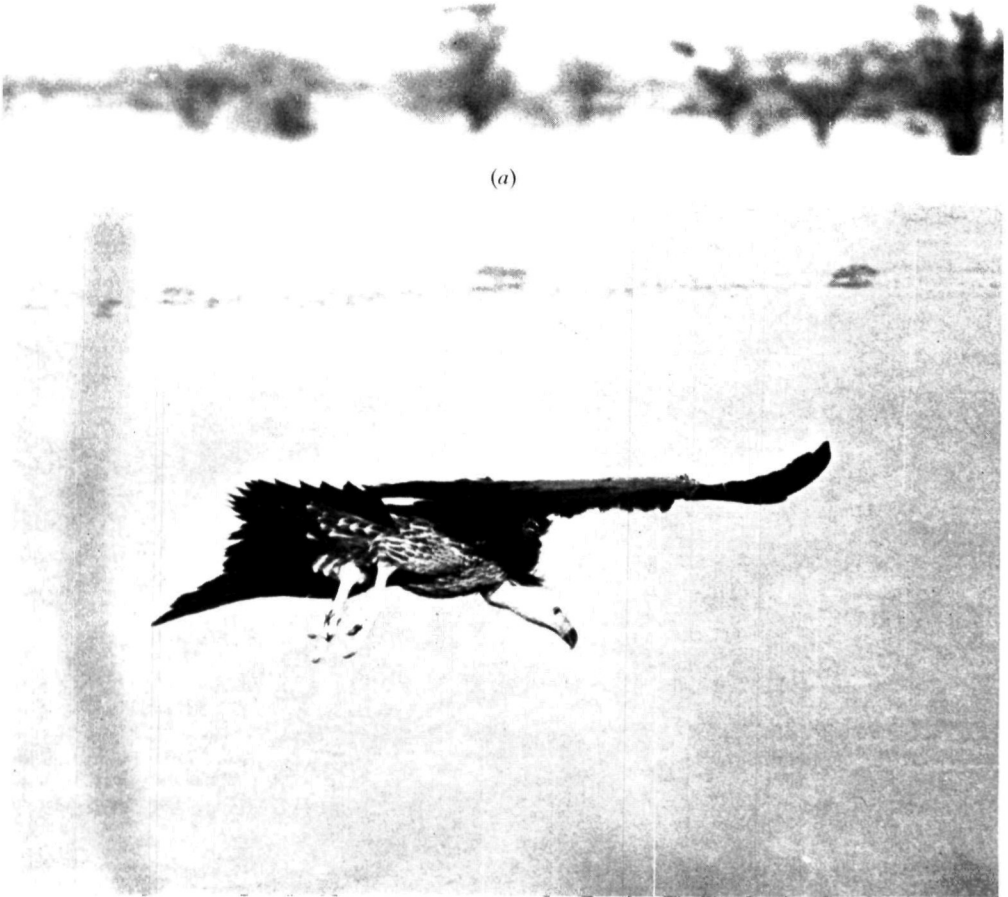
(a) The normal low-speed gliding attitude, with the wings fully spread, neck retracted, and feet furled beneath the tail. (b) In a moderately steep descent, the feet are lowered from the tarsal joints.

PLATE 2

(a) In a steeper descent, the knee and hip joints are also extended, so exposing the tibio-tarsi to the airstream. (b). The raising of the secondaries shown here is seen in very steep descents, especially at low speeds, and is thought to produce an increase in induced drag.



(a)



(b)



(a)



(b)