

## GLIDING FLIGHT OF THE ANDEAN CONDOR IN NATURE

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### INTRODUCTION

The Andean condor (*Vultur gryphus*) is an excellent subject for an analysis of flight. To fly, these big vultures depend on updraughts which in many areas are strongest near cliff faces and canyon walls. From cliffside observation points qualitative aspects of flight by this large bird can be studied in detail at close range while quantitative treatments of flight performance are possible at sites along foraging routes where air movement is steady and easily monitored. This paper presents a quantitative description of the condor's gliding flight as recorded at one of these sites.

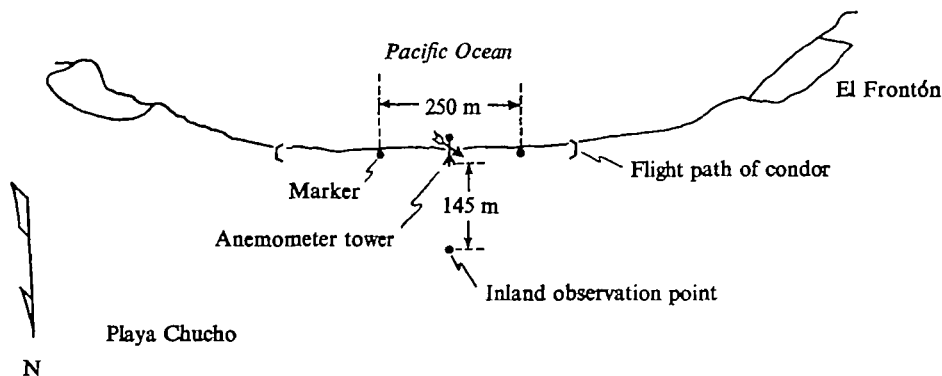
### METHOD

#### *Study area*

All data describing the aerodynamics of gliding flight were recorded at a Peruvian beach, Playa Chucho. This level south-facing beach is located about 30 km south of Pisco and 1 km east of the village Laguna Grande. The beach extends 620 m east-west, separating a series of sandstone cliffs that ascend abruptly to 150 m on the west and slope gradually to a 70 m elevation on the east. Before rising in a series of small hills, 5-15 m high, the beach stretches south into the desert as a flat for 300 m on the west end and 120 m on the east. Condors flying along the coastline crossed the beach in straight smooth flight. At one end of the beach they left declivity currents produced by the cliff-deflected south wind to encounter them again at the other end. This predictable flight path in conjunction with the steady wind characteristic of the Peruvian coast provided an opportunity to measure parameters of their flight.

#### *Procedure*

The observation segment of the beach was marked by two rock piles 60 cm in height and 250 m apart (Text-fig. 1). I stood midway between them and when a condor passed over each marker I recorded the lateral distance to the nearest metre separating the flight path projected on to the beach from the marker. My wife, posted 145 m north of and in line with the tower, recorded the angle of the bird's position above each marker using a sextant mounted on a swivel-head tripod. The sextant, a vertical scale with 80 2.5 mm divisions mounted on a horizontal base 58.5 cm in length, permitted angular measurements used to compute values for altitude to the nearest metre. The tripod and sextant were adjusted so that for each sighting the base of the vertical scale was in line with the top of the marker. For each sighting I used the tangent of the angle recorded with the sextant and the distance measured from the sextant to the flight path projected on to the beach to calculate the altitude of the bird.



Text-fig. 1. The Peruvian observation beach, Playa Chucho.

Considering possible errors in measurement of both angle and distance I estimate each altitude value to be accurate within 3 %.

The duration of the flight interval from one marker to the next was measured to the nearest 0.1 sec with a stopwatch at the inland observation point. Simultaneously, changes in wind conditions were recorded on series of gauges cabled from a 5 m tower standing near the centre of the beach below the flight path. The tower supported a wind vane, a cup anemometer sensitive to horizontal currents and a propeller anemometer sensitive to vertical currents. With data on the velocity of air and bird relative to the ground, I used the law of cosines in a vector analysis to compute values for air speed of the bird. Measured values for the ground distance and time travelled are believed accurate within 2 %, values for wind speed within 20 %, and computed values for air speed of the condor within 4 %.

## RESULTS

For observations on 15 condors (11 males, 4 females) that crossed the beach without flapping during a 13-day period, the mean air speed and computed standard error were  $15 \pm 0.5$  m/sec (Table 1). For 42 condors (23 males and 19 females) that flapped at some point while crossing the beach, the mean air speed and computed standard error were  $14 \pm 0.2$  m/sec. The sine of the condor's glide angle ( $\theta$ ) was calculated by dividing the difference in altitude (i.e. descent or ascent) by the air distance travelled between the two markers. No vertical currents were ever detected by the propeller anemometer, hence no corrections for the distance of vertical movement through the air were made. Values of glide angle  $\theta$  computed for condors that did not flap ranged from a descent of  $3.5^\circ$  to an ascent of  $1^\circ$ . I computed sinking speed with the equation

$$V_s = V \sin \theta, \quad (1)$$

where  $V$  is the air speed. The mean sinking speed and computed standard error for the gliding condors were  $0.5 \pm 0.08$  m/sec. Differences in air speeds and sinking speeds according to sex were not significant. Similar data recorded on five turkey vultures (*Cathartes aura*) are also presented in Table 1.

Table 1. *Flight data from measurements recorded at Playa Chucho*

(Each entry is a mean value followed by a computed standard error.)

	Unit	Gliding condors ( $n = 15$ )	Flapping condors ( $n = 42$ )	Flapping turkey vultures ( $n = 5$ )
Air speed ( $V$ )	m/sec	$15 \pm 0.5$	$14 \pm 0.2$	$10 \pm 0.5$
Sinking speed ( $V_s$ )	m/sec	$0.5 \pm 0.08$	$0.3 \pm 0.04$	$0.4 \pm 0.1$
Sine of glide angle $\theta$	—	$0.030 \pm 0.005$	—	—
Reynolds number ( $\times 10^4$ ) (Re)	—	$3.6 \pm 0.13$	$3.3 \pm 0.06^*$	$1.7 \pm 0.09^*$
Coefficient of lift ( $C_L$ )	—	$0.7 \pm 0.04$	—	—
Total drag ( $F_D$ )	N	$3 \pm 0.6$	—	—
Induced drag ( $F_{Di}$ )	N	$3 \pm 0.2$	$4 \pm 0.2$	$0.7 \pm 0.07$
Horizontal wind speed during observations	m/sec	$5 \pm 0.2$	$3 \pm 0.2$	$2 \pm 0.5$
Initial altitude of flight path	m	$60 \pm 3$	$50 \pm 2$	$30 \pm 4$

\* Does not describe viscous flow regime for those moments during flapping.

### *Aerodynamic relations*

An analysis of the data on forward speeds and sinking speeds considering dimensions of the bird and properties of the air provide standard values useful in evaluating the gliding performance of the condor. Principles involved in such an analysis are discussed in Prandtl & Tietjens (1934). The following relations, conventional for aerodynamical studies, were used:

$$F_D = W \sin \theta, \quad (2)$$

$$F_L = W \cos \theta, \quad (3)$$

$$F_D = \frac{1}{2} S \rho V^2 C_D, \quad (4)$$

$$F_L = \frac{1}{2} S \rho V^2 C_L, \quad (5)$$

where  $F_D$  is the drag force and  $C_D$  the coefficient of drag,  $F_L$  is the lift force and  $C_L$  the coefficient of lift,  $W$  is the weight of the bird,  $S$  is the projected wing area, and  $\rho$  is the air density. In all computations  $\cos \theta$  was taken to be unity; variation from unity is negligible for the small glide angles considered in this study. Size and weight are listed in Table 2. The total weight of the bird will depend to a large extent on the amount of food carried in the crop. The effect of this variable should have been negligible here, however, since crops were empty for 54 of the 57 observations made; only one bird had a full crop. Wing area ( $S$ ) was determined by using a polar planimeter to measure the projected wing area from a photograph taken straight below a gliding condor and multiplying it by the squared ratio of the actual wing-span to the wing-span of the projected image. As total wing area I took the area of the plane projected by both wings together with that part of the body intercepted by straight lines joining the leading and trailing edges of the wing. Length of the average wing chord ( $c$ ) was computed by dividing values for wing area by those of the span. Values used for temperature-dependent air density ranged from 1.18 to 1.20 kg/m<sup>3</sup>. Flow conditions of any fluid around any object can be described by the Reynolds

Table 2. *Dimensions of the condor and turkey vulture*

	Unit	Condor		Turkey vulture*
		Adult male	Adult female	
Mass ( <i>m</i> )	kg	11.7 (4)†	8.4 (2)	1.98 (4)
Wingspan ( <i>b</i> )	m	2.99 (7)	2.77 (3)	1.79 (3)
Wing chord ( <i>c</i> )	m	0.38	0.35	0.26
Wing and intercepted body area ( <i>S</i> )	m <sup>2</sup>	—	—	—
Full extension	m <sup>2</sup>	1.13	0.97	0.46
Moderate flexion (span reduced 20%, Fig. 3)	m <sup>2</sup>	0.95	0.82	—
Wetted areas ( <i>S<sub>w</sub></i> )				
Full extension	m <sup>2</sup>	—	—	1.06
Tail open	m <sup>2</sup>	2.70	2.37	—
Tail closed	m <sup>2</sup>	2.60	2.29	—
Moderate flexion	m <sup>2</sup>	2.23	1.99	—
Aspect ratio ( <i>b</i> <sup>2</sup> / <i>S</i> = <i>R</i> )	N/m <sup>2</sup>	7.9	7.9	7.0
Wing loading ( <i>mg</i> / <i>S</i> )	N/m <sup>2</sup>	102	85	42

\* Sexes similar in size.

† Mean value is computed from sample size listed in parentheses. Data from birds measured in the field are from records taken from the following sources: Apolinar (1914), Murphy (1925), Poole (1938), Fisher (1946), Lint (1960), Conway (1962) and Olivares (1963).

number (*Re*), a dimensionless number that accounts for variations in viscosity effects. Reynolds numbers noted in this study (Table 1) were calculated with the equation

$$Re = Vc(\rho/u), \quad (6)$$

where *c* is the average wing chord length and *u* is the viscosity of the air. Both air viscosity (*u*) and density (*ρ*) are temperature- and pressure-related; in this study the ratio *ρ/u* used varied from 62 500 to 65 400.

The mean and standard error for lift coefficient calculated for the 15 gliding condors were  $0.7 \pm 0.04$ . Lift coefficients are dependent on wing shape and position and describe the effects produced by the angle of attack, the aspect ratio, the profile of the wings, and fluid viscosity of the air. In equilibrium gliding *C<sub>L</sub>* is inversely related to air speed. Condors probably employed a narrow range of optimum speeds in crossing Playa Chucho; I was unable to obtain estimates for minimum and maximum limits for *C<sub>L</sub>*.

Drag forces act to retard forward motion, and in an equilibrium gliding situation the energy required to overcome these forces is equal to the loss of potential energy incurred in the descent through the glide angle (equation 2). These drag forces can be resolved into two types: (1) parasite drag *F<sub>Dp</sub>*, from skin friction and pressure drag, and (2) induced drag, *F<sub>Di</sub>*, caused by the energy loss in producing vortical air movement. I computed estimates for these two types of drag force using a procedure employed by Parrott (1970) in his wind-tunnel analysis of black vulture flight. Induced drag, directly related to lift force, is calculated with the equation

$$F_{Di} = \frac{F_L^2}{\pi \frac{1}{2} \rho (bVM)^2}, \quad (7)$$

where *M*<sup>2</sup>, the Munk span factor, accounts for non-elliptical distributions of lift across the wing. I used a span factor of 0.9, the same value used by Parrott for the

black vulture. I obtained a mean and computed standard error of  $3 \pm 0.2$  N (newtons) for induced drag forces. Estimates for weight and size dimensions used in computing  $C_L$  and  $F_{Di}$  are considered accurate within 5%; values for  $C_L$  are believed accurate within 20%, and values for  $F_{Di}$  within 25%.

By subtracting the values for induced drag from those of total drag, estimates of parasite drag force ( $F_{Dp}$ ) were obtained. Coefficients of parasite drag ( $C_{Dp}$ ) were computed with the equation

$$C_{Dp} = \frac{F_{Dp}}{\frac{1}{2}\rho S_w V^2}, \quad (8)$$

where  $S_w$  is wetted or total surface area of the bird. Values for the wetted area were calculated with a technique devised by Tucker & Parrott (1970), whereby parts of the bird are equated with geometrical figures to secure surface area estimates that are believed accurate within 20% (Table 2).

Data recorded on five turkey vultures presented in Tables 1 and 2 have been treated like the data for condors with one exception. I assumed that the general shapes of turkey vulture and black vulture were similar and estimated the wetted surface area of the turkey vulture by multiplying the value computed for the black vulture (Parrott, 1970) by the squared ratio of wing spans. Since values for the wetted area of the condor determined by this method and the method mentioned above differed only by 1%, I expect the error for the turkey vulture estimate to be insignificant.

Information recorded on condors and turkey vultures that flapped at some time while crossing the observation section of the beach also provided estimates for the forces and coefficients of parasite drag. I corrected sinking-speed values for these data, however, since flapping rate and sinking speed are related (McGahan, 1972). In an analysis of regression with flapping rate as the independent variable I computed mean sinking speeds of 0.5 m/sec for condors and 0.6 m/sec for turkey vultures for a projected flapping rate of zero.

*Parasite drag.* The  $C_{Dp}$  values I obtained for gliding condors were implausibly low. With mean data on air speed and sinking speed I computed a  $C_{Dp}$  of 0.001 for the gliding female condor; for the male I obtained negative values for parasite drag forces, an impossible condition (Table 3).  $C_{Dp}$  estimates from mean data on flapping birds were also low. I calculated 95% confidence limits for the mean air speed and sinking speed observed and combined these upper and lower interval values to secure maximum and minimum estimates for the glide angle, and indirectly the coefficients of parasite drag. So, for example, I divided the lower confidence interval value of 13.6 m/sec for the mean air speed into the upper confidence interval of 0.68 m/sec for sinking speed corrected for zero flapping, to calculate a maximum estimate for the glide angle of flapping condors. For these maximum angles,  $C_{Dp}$  estimates were 0.003 for the flapping male condor, 0.005 for the female, and 0.020 for the flapping turkey vulture. All  $C_{Dp}$  estimates for the condor are exceptionally low, either less than or within the range of optimum values defined for parallel airflow across a smooth flat plate (Table 3). Only the maximum estimate for the turkey vulture approximated to the values determined for the black vulture in Parrott's wind-tunnel study. Apparently some source of error has not been taken into account.

Table 3. *Estimates for the coefficient of parasite drag for condors and turkey vultures*

	Forward air speed (m/sec)	Sinking speed (m/sec)	Sinking speed ad- justed for zero flapping (m/sec)	Sine of glide angle $\theta$	Total drag force (N), eqn (2)		Induced drag force (N), eqn (7)		Coefficient of parasite drag, eqn (8)	
					Male	Female	Male	Female	Male	Female
Mean data for sinking and air speed										
Gliding condors ( $n = 15$ )	15	0.50	—	0.0333	3.8	2.7	3.9	2.4	—	0.001
Flapping condors ( $n = 42$ )	14	—	0.5	0.0357	4.1	2.9	4.5	2.7	—	0.001
Flapping turkey vultures ( $n = 5$ )	10	—	0.6	0.0600	1.2		0.7		0.008	
0.95 confidence intervals for mean air and sinking speeds providing:										
(a) Minimum estimates for $\sin \theta$										
Gliding condors	16.4	0.29	—	0.0177	2.0	1.5	3.3	2.0	—	—
Flapping condors	14.5	—	0.32	0.0221	2.5	1.8	4.2	2.5	—	—
Flapping turkey vultures	11.8	—	0.38	0.0322	0.6		0.5		0.001	
(b) Maximum estimates for $\sin \theta$										
Gliding condors	14.4	0.63	—	0.0438	5.0	3.6	4.3	2.6	0.002	0.003
Flapping condors	13.6	—	0.68	0.0500	5.7	4.1	4.8	2.9	0.003	0.005
Flapping turkey vultures	8.4	—	0.82	0.0976	1.9		1.0		0.020	
$C_{Dp}$ values for airflow parallel to a flat plate calculated for the following Re:								Turbulent flow (Prandtl equation)	Laminar flow (Blasius equation)	
(1) $3.6 \times 10^5$ , the mean Re computed for gliding condors								0.0054	0.0022	
(2) $3.3 \times 10^6$ , the mean Re computed for flapping condors								0.0055	0.0023	
(3) $1.7 \times 10^6$ , the mean Re computed for flapping turkey vultures								0.0064	0.0032	

# DISCUSSION

## Possible sources of error

I found that relatively small errors in the weight estimates for heavier birds produced substantial differences in the  $C_{Dp}$  values. In computing total drag, weight values of the first power are used compared to second-power figures used in calculating induced drag. Thus, if the weight given for female condors is an overestimate of 1 kg or 12% then the  $C_{Dp}$  value for flapping female condors would be twice that shown. An error of similar proportions in the weight of the smaller turkey vulture changed the  $C_{Dp}$  by only 2%. This may help explain why data for the heavier condors, particularly the male, are more deviant.

Two other sources of error could account for the general trend toward low  $C_{Dp}$

values. (1) If a vertical wind component existed in the flight path area above the level of the anemometer tower then the values for glide angle  $\theta$  would be unduly low and would provide underestimates for the total drag as calculated with equation (2). (2) If the assumption of equilibrium gliding were unfounded and condors were decelerating during the period of observation then they could glide at angles less than possible in equilibrium situations. A third possibility, where glide angle is reduced by an acceleration of wind acting in concert with inertial forces, is unlikely since the velocity of the even coast wind varied little if at all across the short span of the flight intervals.

To obtain expected values for total drag force I calculated new values for parasite drag with equation (8) using a modified  $C_{Dp}$  value derived for the black vulture (Parrott, 1970). Although  $C_{Dp}$  values for the black vulture were secured at Re values lower than those recorded for the condor I adjusted the  $C_{Dp}$  value according to the factor  $K$  (Tucker & Parrott, 1970) for Re values that ranged from  $3.3 \times 10^5$  to  $3.6 \times 10^5$ . The factor  $K$  is a ratio of  $C_{Dp}$  for the bird to that of a flat plate in parallel but turbulent airflow at a given Re value. I multiplied a  $K$  value of 2.2 derived for the black vulture (Tucker & Parrott, 1970; Parrott, 1970) by the  $C_{Dp}$  value for a flat plate at the Re computed for gliding and flapping condors (Table 3) to secure an adjusted  $C_{Dp}$  of 0.012 for the condor. For the turkey vulture I used a  $C_{Dp}$  of 0.015, a value midway between the extremes obtained for the black vulture since the Re for the turkey vulture were within the range noted in Parrott's study.

Parasite drag forces computed with these data provided corrected mean values for total drag of 3.6 and 4.4 N for flapping and gliding condors, respectively (Table 4). According to the changes adjusted for drag the mean glide or  $L/D$  ratio became 14 compared to the observed mean ratio of 33. With equation (2) I computed values for a vertical wind component that would account for the difference in observed and hypothetical drag values. Using the relation

$$F_D = W \sin \theta - ma = mg \frac{V_s}{V_f} - ma, \quad (9)$$

where  $m$  is mass of the bird and  $a$  is acceleration in the direction of the flight path I derived the relation

$$V_s = V_f \frac{F_D}{mg} + V_f \frac{a}{g}. \quad (10)$$

For each observation the observed value for  $V_s$  was less than the corrected one. In a search for clues to detect the source of error I assumed that one of two conditions operated: (1) a vertical wind component existed that was equal to the difference between observed and expected sinking speeds in each observation or (2) the condor decelerated. If all discrepancy was due to deceleration then each unit of vertical wind component satisfying the discrepancy could be translated to units of deceleration according to the relation expressed by the last term of equation (10). Then, to find which error might have operated I compared the amount of vertical wind or deceleration satisfying drag discrepancy with certain other variables.

Three hypotheses were presented. (1) An undetected vertical component for wind above the tower should be stronger when the horizontal wind velocity increased. If this error contributed the discrepancies would be positively related to the horizontal

Table 4. *Values describing certain parameters of flight that are adjusted to satisfy a discrepancy in estimates of drag*

(Each entry is a mean value followed by a computed standard error.)

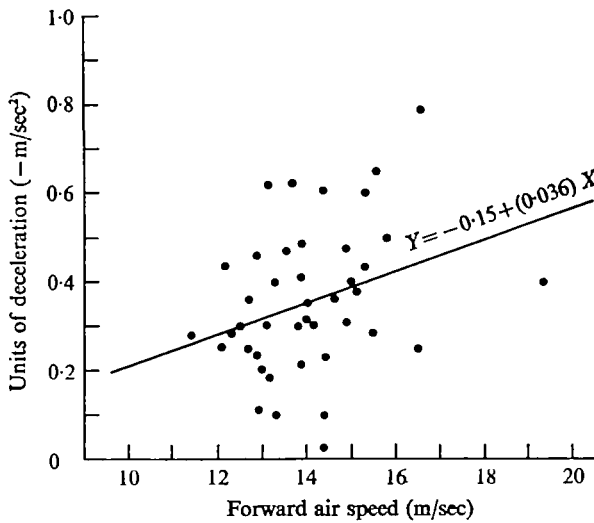
	Unit	Gliding condors ( $n = 15$ )	Flapping condors ( $n = 42$ )	Flapping turkey vultures ( $n = 5$ )
Parasite drag ( $F_{Dp}$ )	N	$4.4 \pm 0.3$	$3.6 \pm 0.1$	$1.0 \pm 0.1$
Total drag ( $F_D$ )	N	$7.7 \pm 0.3$	$7.3 \pm 0.2$	$1.7 \pm 0.04$
Sine of glide angle $\theta$		$0.073 \pm 0.0005$	$0.073 \pm 0.0005$	$0.087 \pm 0.002$
Vertical wind component	m/sec	$0.7 \pm 0.08$	$0.5 \pm 0.04$	$0.3 \pm 0.05$
Deceleration	m <sup>2</sup> /sec	$0.4 \pm 0.05$	$0.4 \pm 0.03$	$0.3 \pm 0.03$

wind speed. (2) Decelerating condors probably reduce their forward speeds to an optimum level for crossing the beach. Hence I would expect birds flying faster to decelerate more on the average, predicting a positive correlation between values for deceleration and air speed. (3) Condors could glide at steeper angles to attain above-average speeds. If most of the condors started at comparable altitudes then those decelerating after gliding temporarily at a steeper angle would start across the beach at a lower initial altitude. A negative correlation between the discrepancy for drag forces and the initial altitude of flight would serve as evidence for the presence of deceleration forces. One of the 15 gliding condors actually gained altitude while crossing the beach; this bird also started at the lowest altitude, 39 m. The condor may have dropped sharply just before entering the observation section and then, while decelerating, crossed it without descending – a typical pelican flight pattern seen when they skim along just above the water surface without flapping.

No correlations were significant for the data on the 15 gliding condors. For the flapping condors I used a regression coefficient for flapping rate and sinking speed (McGahan, 1972) to correct the vertical wind and deceleration units to levels of zero flapping. Then with these corrected values I computed correlation coefficients with the same variables used with the gliding condor data. First, I examined the association between the flapping rate and each of the test variables to check for any bias introduced by the correction factor for flapping. The correlations were not significant and in each case the bias acted to retain the null model. For units of deceleration satisfying the apparent drag discrepancy I obtained a negative correlation with the altitude of the flight path ( $r = -0.13$ ) and a positive correlation with flight speed that was significant (Text-fig. 2). The significance of the last coefficient provides some evidence that deceleration was responsible for the low values of  $C_{Dp}$  I obtained.

Although this analysis provided no evidence for the presence of an undetected vertical wind component, one field observation did. A turkey vulture turned around twice within the central third segment of the observation beach, glided above me three times without flapping during a 1 min period, and lost only 5–10 m of altitude. The horizontal anemometer recorded a wind speed of 8 m/sec but the vertical anemometer registered nothing. Deceleration in this case could not explain the unusually low sinking speed; a vertical wind component must have been present above the tower.





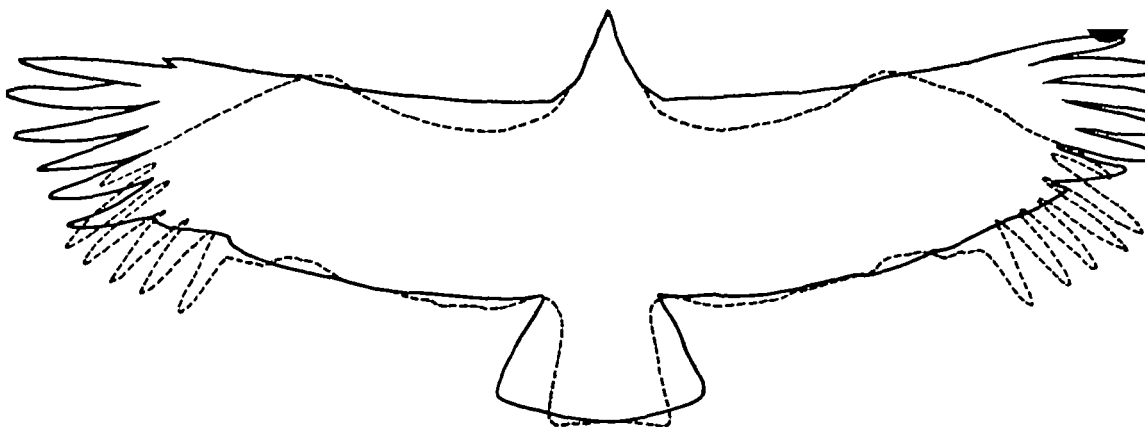
Text-fig. 2. Air speed of condors that flapped while crossing Playa Chucho related to units of deceleration that satisfy an apparent discrepancy in computed values for drag ( $n = 42$ ,  $r = +0.32$ ,  $P < 0.05$ , 1-tail test).

An average difference of  $8^\circ$  in the angle of streamlines in the boundary layer at the level of the tower and the flight path could account for the theoretical discrepancy in the drag forces for the gliding condors. By dividing 5 m/sec, the mean horizontal wind speed for the observations (Table 1), into 0.7 m/sec, the mean vertical wind component expected (Table 4), I obtained an estimate of the tangent of the streamline angle necessary to explain the drag differences. A similar computation using 0.5 m/sec, an expected value for the vertical wind in the absence of flapping, and 3 m/sec, the mean horizontal wind speed, for observations of flapping condors provided an estimate of  $10^\circ$  for the difference in streamline angles. From data on flapping turkey vultures I obtained a value of  $9^\circ$ . These three sets of data recorded during periods with generally different wind conditions provided three similar estimates. This hypothetical flow pattern for different levels in the boundary layer of air striking a coastline would not be unusual.

### *Flex-gliding*

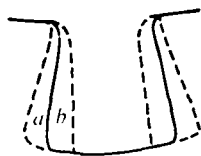
Flex-gliding, a term from Hankin (1913), designates a gliding posture where the wings are partially flexed in the horizontal plane. In bending both wrist and elbow condors altered the wing configuration across a range from near full extension to some positions where the span was almost halved (Plate 1C). Moderate flexion characterized smooth straight gliding journeys over long cross-country distances. Wing area is reduced by overlapping the primaries in flexing the manus and by relaxing the patagium in bending the elbow (Text-fig. 3). Simultaneously the tail usually contracts to a more closed position. Circling condors generally initiated long cross-country flex-glides with a dipping motion by both manus; then, the wings and tail, which were expanded during the circling ascent, moved to the flexed position as the bird began the straight descending glide.

Many of these straight flights, uninterrupted by bouts of flapping or circling,



Text-fig. 3. Differences in the flexed and extended gliding postures. Span in flexed posture is reduced by 20 %. Traced from photographs.

Frequency of tail  
expansion postures  
about an intermediate  
zone  
(see sketch)



(a) Expanded more  
(b) Expanded less

Air speed	
$\leq 16$ m/sec	$> 16$ m/sec

28

20

1

8

$\chi^2 = 6.76$   
 $P < 0.01$

Text-fig. 4. The degree of tail expansion related to air speed for 57 condors crossing Playa Chucho.

extended over periods of 5 min. Recorded durations of four flex-glides were particularly long: 7 min 40 sec, 9 min 42 sec, 12 min, and 14 min 40 sec. In the last observation the condor, before disappearing in the distance, had traversed about 13 km ground distance and had lost only one-fourth of the 1000 m altitude gained in a circling bout prior to the flex-glide. Hypothetically, if the bird continued to encounter the same air conditions he could have travelled 50 km in a period of about 35 min, a potential journey made possible by ascent in a circling bout only 8 min in duration. In this particular observation I was standing below the midpoint of the flight path described. Values for altitude were obtained by combining estimates of the angle of the bird's position above certain mountains or ridges with data from maps on the altitude of the landmark and its distance from the observation point. I was often able to determine the bird's position relative to the landmark by locating the bird's shadow on the ground and then using the sun's 'line of sight' for triangulation.

The forward air speeds of condors in a moderately flexed posture should exceed those of condors gliding with fully extended wings. In an equilibrium gliding system a reduction of airfoil area coincides with an increase in velocity. I noted that the tails of condors crossing the observation beach at higher air speeds tended to be less expanded (Text-fig. 4).

Assuming that the condor seeks to minimize sinking speed, then velocity increases brought about by wing flexion can be computed with the equation

$$S = 2mg (M^2/\pi RCD_0)^{1/2}/\rho V^2 \quad (11)$$

provided by Alexander (1968), where  $R$  is the aspect ratio and  $C_{D_0} = C_{Dp} (S_w/S)$ , a parasite drag coefficient for wetted surface in terms of the projected wing area. I used an air density value  $\rho = 1.18 \text{ kg/m}^3$ , a parasite drag coefficient  $C_{Dp} = 0.012$ , and the mean dimension values for male and female condors given in Table 2 to compute estimates for the air speed of condors in the two flight postures shown in Fig. 3.

According to these computations an adult male with wings fully extended would glide with minimum sinking speed when his forward air speed was 13.9 m/sec. Upon flexing them to the degree shown in Text-fig. 3 (a span reduction of 20%) this optimum forward air speed would increase to 15.2 m/sec. Corresponding values for the adult female are 12.6 and 13.8 m/sec, respectively. These figures can serve only as rough estimates, however, since  $C_{Dp}$  variation at different speeds is neglected as well as airfoil effects of the tail.

An ability to change forward air speed provides the condor with a flexibility for crossing areas that differ in the types of air movement, food availability and potential danger. Efficient increases in air speed are necessary for flight against a headwind; the condor must sacrifice the shallow glide angle of a moderate air speed for a speed providing some forward progress relative to the ground. As air speed increases the condor can minimize increased sinking speed by reducing airfoil area. Once I saw an adult female circling in a 40 km/h wind flex her wings and tail more while travelling upwind than downwind, apparently accelerating upwind flight to reduce ground speed downwind. Five condors flushed from a cliffside roost circled up about 500 m above the sea and then, in postures flexed to the degree shown in Text-fig. 3 (dotted line), glided in steep descent south-east along the coast heading against an evening cross wind of 30 km/h. Ground speeds were noticeably reduced compared to those observed when wind speeds were less. Every 20–30 sec each bird flapped in a bout of three wing-beats. Presumably these bouts served to reduce sinking speed (McGahan, 1972) and thus extended the potential endpoint of the descending flight path farther up the coast.

Frequently, condors flying in intense declivity winds near cliffs glided with strongly flexed wings and lowered feet (Plates 1 A, C, 2). This posture occurred in flight patterns preceding landing and often during periods when the birds flew near my observation point and inspected me carefully. Fluttering wing covert feathers (Plate 2) and raised alulas (Plate 1 A) indicate that the angle of attack with the steep vertical wind is large enough to detach part of the boundary layer of air moving over the wings. These stalling effects coincide with an increase in sinking speed and a reduction in forward speed. Lowered feet can function as air brakes to retard forward air speed. In an air mass that ascends rapidly the bird is permitted greater sinking speeds without losing altitude; then, the reduction in forward speed can augment conditions for examining objects on the ground, enhance the precision of landing manoeuvres, or provide prolonged access to local declivity currents of limited size. I watched an adult male advance with a fairly constant ground speed of only 0.5 m/sec for several minutes while flex-gliding near the edge of a cliff in a 35 km/h headwind. Another adult male

in a 30 km/h headwind both advanced and ascended at the rate of 0.3 m/sec. One condor, flex-gliding in a deflexion current, maintained a high pitch angle of 35° and climbed in steep almost vertical ascent without stalling. Sometimes in strong deflexion currents condors with fully extended wings made little forward progress relative to the ground for extended periods; in one instance a condor, apparently gliding in the updrafts of a beach-deflected wind, did not move, except for a gradual descent during a 40 sec period. Then she glided downwind, ascended near the face of a bluff, and returned again to assume this stationary glide above a carcass on the beach. Advancing slightly, another condor descended for 1 min at a mean rate of 2.4 m/sec in a straight path that formed a 70° angle with the ground. The wings were completely extended and pitch was parallel to the horizon.

Increasing the weight loading ratio of the airfoil by flexion may have functioned at times to provide more stability for condors flying in turbulent updrafts. In pursuits and in flight patterns in restricted areas temporary flexed-wing postures provided manoeuvrability. Acceleration forward and down succeeded wing flexion, and deceleration succeeded extension. Sometimes circling condors alternated between extended and flexed wing postures; in alternating between altitude gains and losses they tended to remain in the same general area for extended periods. Eight times an immature female alternately ascended and descended in a coastal declivity current. Flexing her wings to half span and simultaneously lowering her feet she began a descent losing about 10 m altitude; then, extending her wings fully and lifting her feet back to the position against the body she initiated the ascent that carried her back to the original level. This series of manoeuvres was conducted while circling in the same general area.

#### SUMMARY

1. Derived in a vector analysis with measurements of wind velocity and ground velocity of the bird, the following mean air speeds were obtained for birds crossing a Peruvian beach: 15 m/sec for 15 gliding Andean condors, 14 m/sec for 42 condors that flapped during the crossing, and 10 m/sec for five turkey vultures that flapped. For the 15 gliding condors a mean lift coefficient of 0.7 and a mean induced drag force of 3 N were computed.

2. Implausibly low values derived for parasite drag coefficient of the condor appeared to be due to (a) unmeasured forces of deceleration and (b) an undetected vertical component of the wind at the level of the flight path. Field data, adjusted by introducing a coefficient of parasite drag determined for the black vulture in a wind-tunnel study provided corrected estimates of drag. I secured an adjusted value of 14 for the  $L/D$  ratio of a condor gliding with wings fully extended.

3. A moderate flexion of the wings reducing the span by 20% is estimated to increase the optimum air speed from 13.9 to 15.2 m/sec for an adult male condor and from 12.6 to 13.8 m/sec for an adult female.

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A



B



C<sub>2</sub>



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