

INDUCED DRAG SAVINGS FROM GROUND EFFECT AND FORMATION FLIGHT IN BROWN PELICANS

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SUMMARY

Ciné films of brown pelicans flying in formation were used to measure altitudes and wing tip spacing (WTS, distance perpendicular to the flight path between wing tips of adjacent birds at maximum span) for birds flying in ground effect, and vertical displacements and WTS for birds flying out of ground effect. Views were near coplanar with the plane of flight paths, and maximum wing span was used for scale. Induced drag savings in ground effect averaged 49% for gliding. Average WTS varied considerably with no evidence for systematic positioning near an optimum. There were also no differences in average WTS between flapping and gliding in or out of ground effect. Vertical displacements out of ground effect varied less than WTS but more than vertical displacements in ground effect. Few birds had wing beat frequencies similar to the bird ahead as would be needed to track vertical variation in trailing wing tip vortex positions. Imprecision in WTS may be due to unpredictable flow fields in ground effect, and difficulty in maintaining position under windy conditions out of ground effect.

INTRODUCTION

Some behavioural adaptations proposed for locomotion involve interference effects among individuals in a group or between individuals and a surface. These include formation flight in birds (Lissaman & Schollenberger, 1970; Hummel, 1983; Hainsworth, 1987), schooling in fish (Weihs, 1973; Abrahams & Colgan, 1985), movement in a queue (Bill & Hernnkind, 1976) and flight with 'ground effect' (Blake, 1983; Withers & Timko, 1977). In black skimmers (*Rhyncops nigra*) ground effect was estimated to reduce induced drag by 50–90% (Withers & Timko, 1977). In Canada geese (*Branta canadensis*) formation flight was estimated to reduce induced drag by 30–40%, although there was considerable variation (Hainsworth, 1987).

Savings from ground effect and formation flight depend on spacing in different directions. For ground effect, altitude from a surface relative to wing span determines induced drag savings (Fig. 1):

$$1/e = (16A/b)^2/[1+(16A/b)]^2,$$

Key words: adaptations, behaviour, energetics, formation flight, ground effect, locomotion, vortices.

where A is altitude, b is wing span, and $1/e$ is coefficient of induced drag with ground effect/coefficient of induced drag without ground effect (Spedding, 1987a; McCormick, 1979). For formation flight, lateral spacing of a wing tip from the centre of a trailing wing tip vortex determines induced drag savings (Fig. 2). A pair of fully formed trailing vortices are located $\frac{1}{2}\pi b$ apart behind a fixed wing of span b ; savings also depend on the number of birds in formation (Fig. 2; Lissaman & Schollenberger, 1970).

Models of both mechanisms assume a fixed wing. Birds which fly close to surfaces often glide without loss of altitude (Withers & Timko, 1977; Blake, 1983); predictions from aircraft aerodynamic models are probably directly applicable to gliding flight of birds (Spedding, 1987a). Spanwise vorticity is continuous for birds and bats in moderate to fast flapping flight, but trailing vortices vary in position vertically and horizontally owing to wing movements (Spedding, 1987b; Rayner, Jones & Thomas, 1986). This variation has not been considered in models or measurements of formation flight or flight with ground effect.

Brown pelicans (*Pelecanus occidentalis*) sometimes fly in formation, and some formation flight occurs close to the water. During formation flight the birds periodically flap and glide (O'Malley & Evans, 1982; personal observations). Altitudes close to the water and wing tip spacing (WTS, distance perpendicular to the flight path between wing tips of adjacent birds at maximum span) were measured for brown pelicans during flapping and gliding in and out of ground effect to estimate contributions of ground effect and formation flight to induced drag savings.

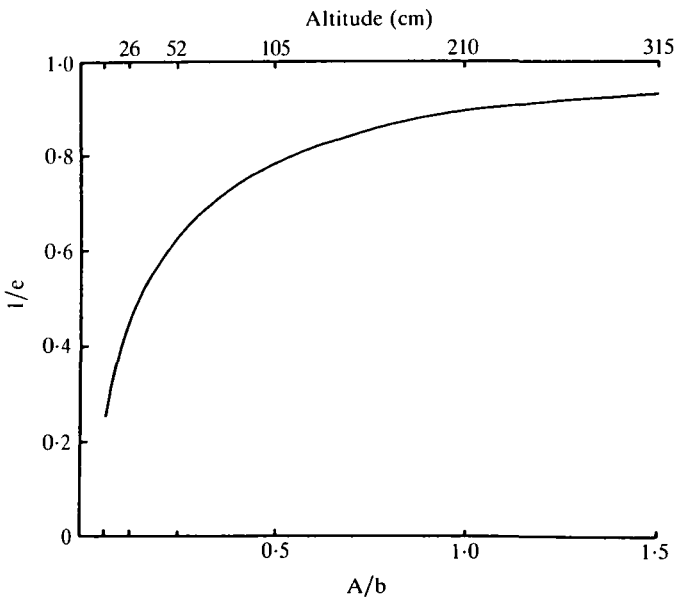


Fig. 1. Coefficient of induced drag in ground effect/coefficient of induced drag out of ground effect *versus* the ratio of altitude (A) to wing span (b). The upper abscissa gives altitudes for a brown pelican assuming $b = 210$ cm. The line is from the equation in the text.

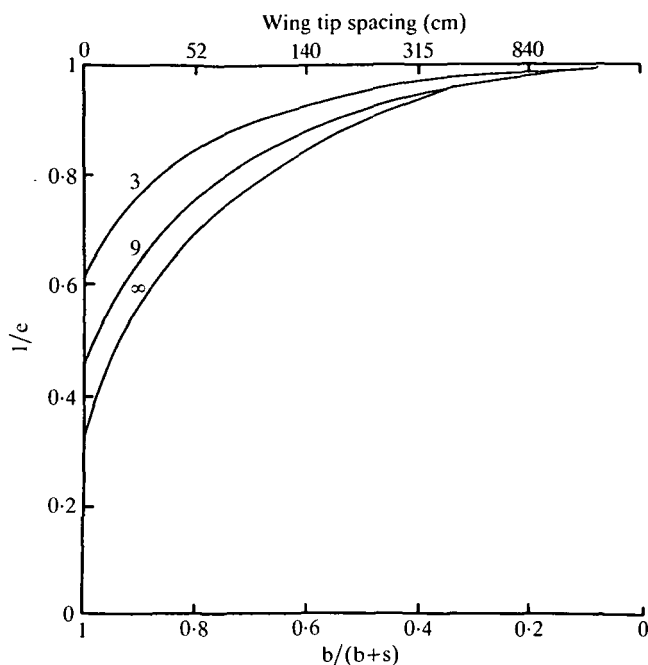


Fig. 2. Coefficient of induced drag in formation/coefficient of induced drag for solo flight *versus* the wing tip spacing index $R = b/(b+s)$ (b is wing span, s is wing tip spacing) (from Lissaman & Schollenberger, 1970). Numbers above lines are numbers of birds in formation. The upper abscissa gives wing tip spacings for brown pelicans assuming $b = 210$ cm.

MATERIALS AND METHODS

Pelicans were filmed and maximum wing span was used to correct for distance. A maximum span of 210 cm was used, based on measurement of a bird by Pennycuik (1983) and a carcass with primary feathers attached found on Marco Island, Florida. To minimize perspective distortion, birds were filmed only if they passed over the camera and continued in a straight path away from the camera. The camera was placed on the fishing pier below the C951 bridge to Marco Island. The pier was located about 1 km west of the Bird Islands, a cluster of mangrove islands in the Marco River used by brown pelicans for roosting and nesting. Birds would leave or approach the islands by flying along the southern edge of the Marco River where the camera was located. Films were taken after the birds had passed overhead when it was judged that the flight path was directly away from the camera. Films (16 mm) were taken at $32.8 \text{ frames s}^{-1}$ using a zoom, telephoto lens with maximum focal length of 210 mm. Film speed was calibrated by photographing a stopwatch.

Errors could occur from two sources. First, the sample size for estimating average maximum wing span is small. Second, although filming was limited to formations passing over the camera, there was probably some variation in the angle of the line of sight of the camera so it may not always have been exactly perpendicular to wing

span. Image wing span length varies by a factor equal to the sine of the angle of the line of sight to the wing span, and when wing spans were not exactly perpendicular to the camera line of sight this was less than one. However, even with a deviation as large as 20° from a perpendicular line of sight, the estimates of length would be within 94% of values at the perpendicular. Errors in estimating altitudes and vertical displacements would likewise depend on deviation of the angle of the line of sight from horizontal. The declination of the camera never exceeded 7° for films of birds flying close to the water, and camera inclination never exceeded 20° for films of birds flying out of ground effect.

Up to five altitudes and spans were measured for each of 23 birds flying close to the water with measurements at 3- to 4-s intervals. For individuals flapping their wings I selected frames where span was maximum to correct altitudes for distance. Altitudes were measured from the centre of a bird's body (the approximate vertical wing tip position during gliding) to the surface of the water. The reflection of the bird was used to define the appropriate point on the water surface for these measurements.

Wing movements during a wing beat cycle were examined by superimposing tracings of wing outlines frame-by-frame for a representative bird. These were used to measure changes in span and vertical positions of the outer wing extremities relative to the bird's centre point.

Wing tip spacing was measured from the corrected horizontal distance between centre points of adjacent birds minus a wing span of 210 cm (Hainsworth, 1987). Maximum wing spans for images of each bird in formation were measured for frames closest to the 1 s interval frames selected for measuring WTS, and the average image span was set to 210 cm. 286 values of WTS were measured for 24 trailing birds out of a total of 41 birds in 14 formations. There were eight formations of two birds, four of three birds, and one each of four and six birds, so formation size was small compared with other species (O'Malley & Evans, 1982; Hainsworth, 1987). Six formations flew close to the water; eight flew out of ground effect. Film times varied from 3.1 to 18.3 s and totalled 134.8 s.

Models of formation flight assume all individuals fly in the same horizontal plane. Measurements of altitudes close to the water give information on variation in vertical positions, but the surface may constrain variation. Vertical displacements from centre points of adjacent individuals were measured for individuals in the eight formations flying out of ground effect using maximum wing spans for scale. Vertical displacements were measured for each frame measured for WTS.

Since the view of formations was close to coplanar with the plane of flight paths, the depth between birds (distance between adjacent birds along the flight path) could not be measured. Information on depth is useful to test for wing positioning of trailing individuals with respect to vertical variation in position of trailing vortices from wing movements of the bird ahead. For birds to track vertical vortex position variation, relative wing position should depend on depth. For example, wing position of a trailing bird should be synchronized with the bird ahead when it is positioned at a depth of one period, or multiples of one period, in vertical vortex

position variation behind the bird ahead. However, for an individual to utilize this variation it must also have the same wing beat frequency as the bird ahead. Wing beat frequencies were compared using the methods described by Berger (1972). The number of frames for a complete wing beat was measured for a series of wing beats (between glides) for each individual, and the modal number of frames beat⁻¹ was determined for a formation. A coordinate system was constructed with frame number (time) on the ordinate and frames of difference from modal frames beat⁻¹ on the abscissa. A point for a wing beat at the frame number for maximum wing elevation was plotted directly below the preceding point when frames beat⁻¹ equalled the modal value; it was placed n frame units to the right if it exceeded the modal value by n frames (lower frequency), and it was plotted n frame units to the left if it was less than the modal value by n frames (higher frequency) (Berger, 1972). Wing beat frequencies were compared when slopes of these plots were uniform, i.e. lacking sharp discontinuities in wing beat frequencies.

RESULTS

Ground effect

Fig. 3 shows frequency distributions for altitudes (assuming maximum span = 210 cm) for brown pelicans during gliding (open histogram) and flapping (shaded histogram). The average altitude during gliding was 33 ± 5 cm (s.d., $N = 41$) and the average altitude during flapping was 52 ± 10 cm ($N = 58$) ($t_{97} = 10.614$, $P < 0.001$). Fig. 1 shows that gliding at an average altitude of 33 cm yields an induced drag saving of 49%. The extremes of variation in altitude during gliding (24–45 cm) would give induced drag savings ranging from 41 to 58%.

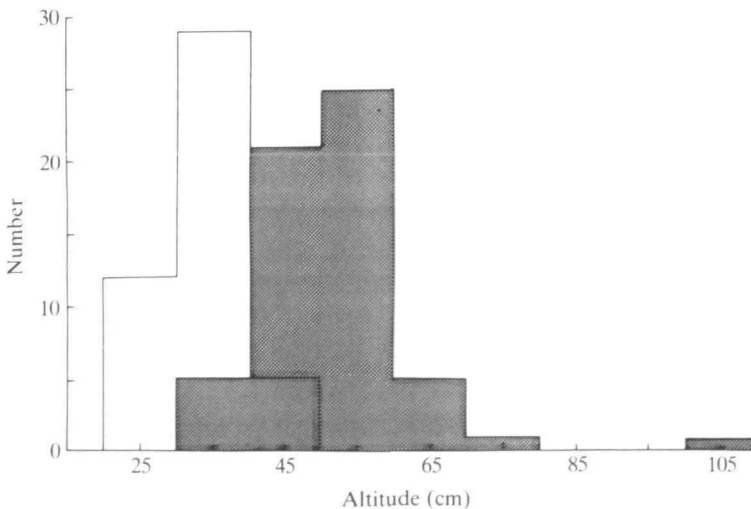


Fig. 3. Frequency distributions for altitudes of brown pelicans while gliding (open) and flapping (shaded) close to the water.

Fig. 4 shows changes in wing positions during a wing beat cycle. Maximum span was at mid-downstroke (frame 5 in Fig. 4), and the outer portion of the wing was flexed during the upstroke (Figs 4, 5). This pattern is similar to those described for kestrels (*Falco tinnunculus*; Spedding, 1987b) and bats (Rayner *et al.* 1986) at moderate to high flight speeds where vortex visualization indicated constant circulation with time because of changes in wing geometry. Changes in wing extremity vertical displacement showed a sinusoidal variation (Fig. 6), with the extremities about 10 cm from the water at the end of the downstroke, based on the average altitude during flapping. Altitude variation during flapping (range

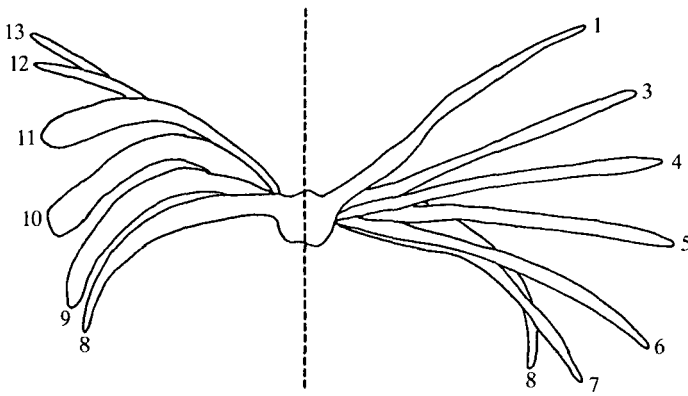


Fig. 4. Tracings of wing positions during a wing beat cycle for a representative bird. Downstroke is on the right, upstroke on the left. Numbers are frame numbers (film speed = $32.8 \text{ frames s}^{-1}$).

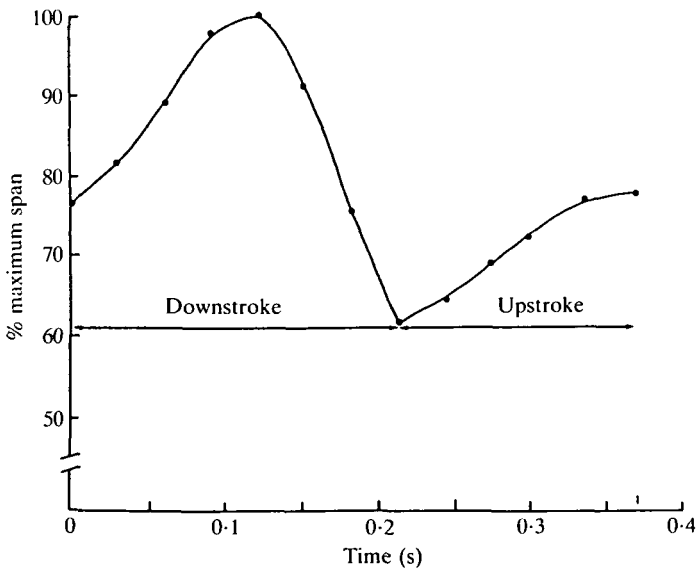


Fig. 5. Changes in span during a wing beat cycle for a representative bird. Each point is a measurement for successive frames. The line was drawn by eye.

35–100 cm) would place wing extremities in the water at low altitudes at the end of a downstroke unless the downstroke was modified.

It is difficult to estimate ground effect during flapping because models are based on the relatively simple case of a fixed wing (Spedding, 1987a). Gliding at the average flapping altitude of 52 cm would have produced a saving of 36%, and it is likely that some appreciable saving occurs during flapping, even though it cannot be estimated precisely.

Formation flight

There was considerable variation in WTS among individuals (Fig. 7). Most variation was due to maintenance of different mean spacings by individuals (Fig. 8). Average WTS ranged from -171 ± 32 (s.d.) to 183 ± 45 cm. Standard deviations ranged from ± 18 to ± 80 cm. There was little to suggest a clustering of individuals at a particular WTS, such as the -22 cm position predicted for the location of the centre of a trailing vortex behind a fixed wing of span 210 cm (Figs 7, 8). Six of the 24 birds had average values of WTS \pm s.d. which included the -22 cm location. Three of these flew in ground effect and three flew out of ground effect.

Pelicans flew out of ground effect when it was windy, and they flew close to the water when it was calm and the water surface was smooth. Thus, it might be

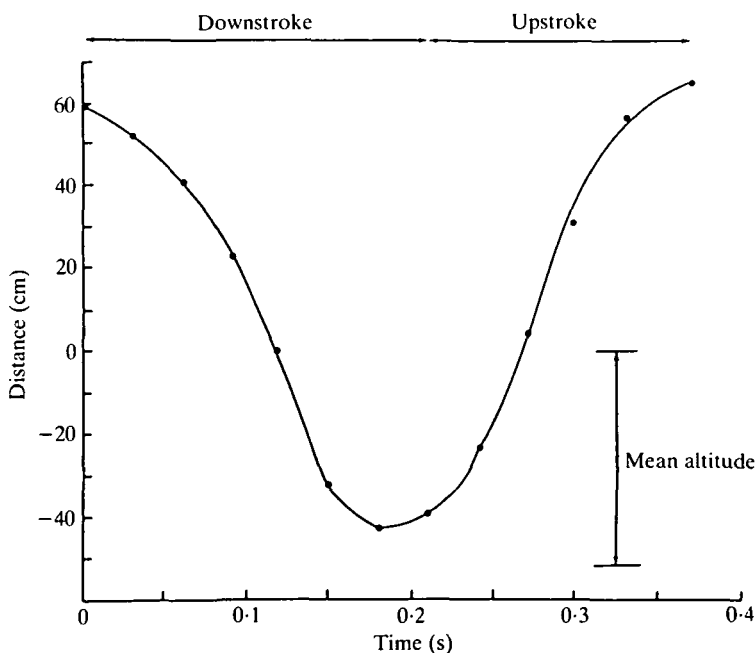


Fig. 6. Vertical movements of wing extremities relative to the centre of the body (0 cm) during a wing beat cycle for a representative pelican. The ordinate scale is based on a maximum span of 210 cm. Each point is a measurement for successive frames. The line was drawn by eye. Mean altitude during flapping close to the water was 52 cm.

expected that WTS could differ for birds flying in ground effect compared with out of ground effect. This was not the case. The average WTS for measurements in ground effect was -15 ± 134 cm compared with -7 ± 116 cm for measurements for birds flying out of ground effect ($t_{281} = -0.526$, $P = 0.60$).

Wing movements during flapping should produce variation in trailing vortex positions compared with gliding (Spedding, 1987*a,b*). To test for possible effects on positioning, mean WTS when all the birds of a formation were gliding was compared

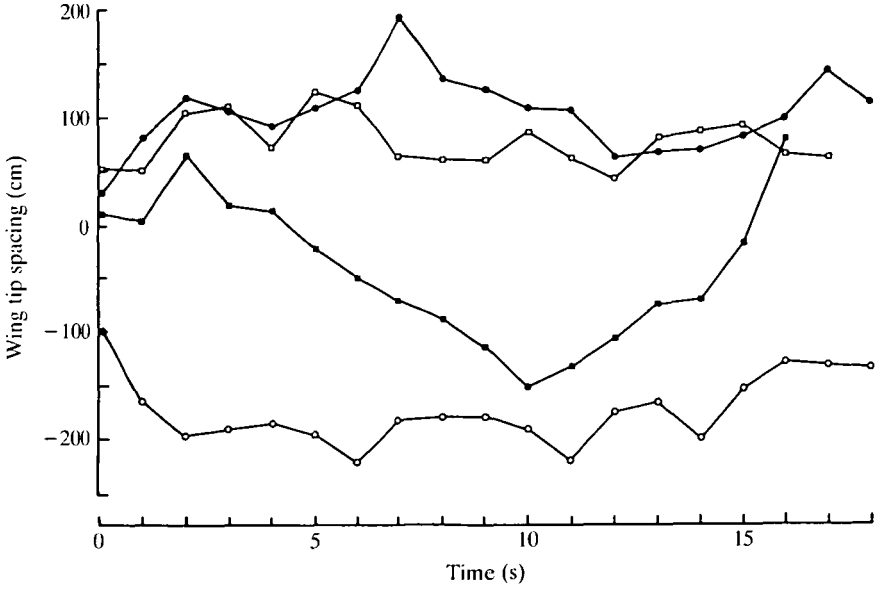


Fig. 7. Wing tip spacings as a function of time for four pelicans flying in formation.

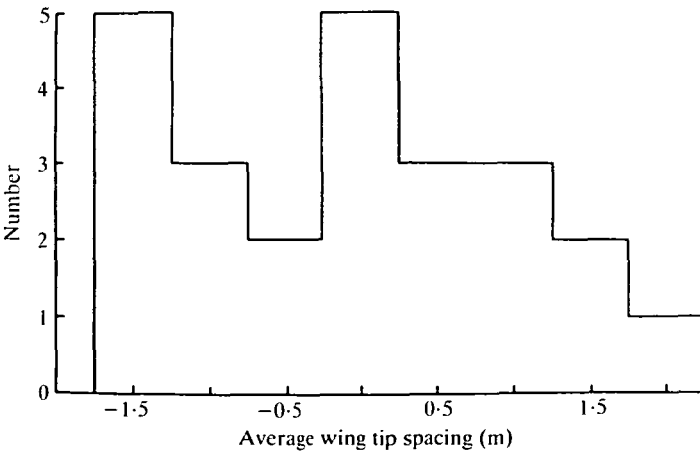


Fig. 8. Frequency distribution of average wing tip spacings for 24 pelicans flying in formation.

with mean WTS when all were flapping. The averages were not significantly different ($t_{201} = 0.898$, $P = 0.37$). Mean WTS for flapping birds was also compared with mean WTS for gliding birds, after separating the data into values for birds flying in and out of ground effect. These averages were also not significantly different (in ground effect $t_{125} = 0.437$, $P = 0.65$; out of ground effect $t_{72} = 0.368$, $P = 0.67$). There were also no significant differences when comparing mean WTS for birds gliding in ground effect with those gliding out of ground effect ($t_{116} = -0.271$, $P = 0.69$) or flapping in ground effect with those flapping out of ground effect ($t_{81} = -0.218$, $P = 0.68$).

Vertical displacements out of ground effect showed greater variation than those near the water but less variation than that in WTS among individuals (Fig. 9). The distribution was negatively skewed, with a few measurements up to 2 m below the bird ahead. About half the values were above zero (54) and half below (52), with a median of -3 cm and quartile deviations from -49 to 28 cm (Fig. 9). There was no significant difference between vertical displacements when all the birds were gliding or when all were flapping (Mann-Whitney U -test, $Z = -0.29$, $P = 0.689$).

Fig. 10 shows an example of a plot used to compare wing beat frequencies of adjacent birds. Comparisons were made when slopes were uniform and both birds were flapping for at least 10 beats; this gave nine comparisons (Table 1). Although differences do not appear large, even small differences would result in changing phase relationships between wings of adjacent birds. Unless depth also varied, wings of trailing birds would not track vertical vortex position variation as phase relationships changed. Only three birds had differences close to zero (Table 1). One

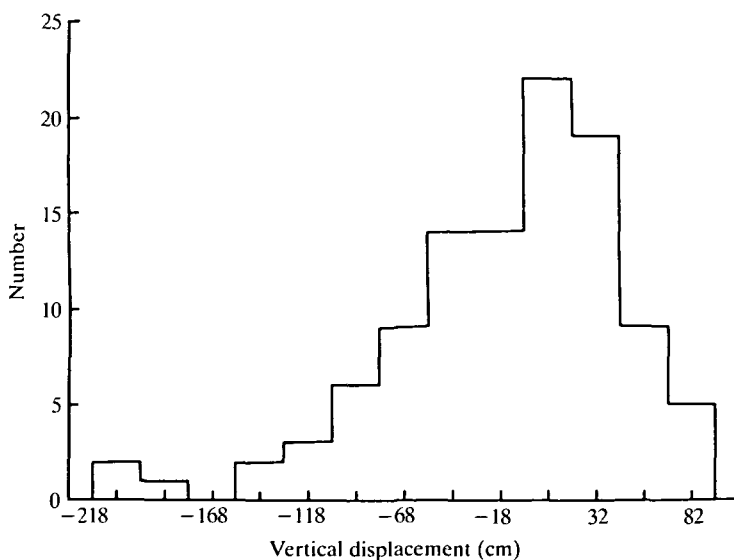


Fig. 9. Frequency distribution of vertical displacements of adjacent birds (measured from bird centre points) for pelicans flying out of ground effect.

of these (difference = $0.04 \text{ beats s}^{-1}$) was a bird with average WTS close to the optimum.

DISCUSSION

Pelicans achieve substantial energy savings from ground effect. Total metabolic expenditures are considerably reduced during gliding (Baudinette & Schmidt-

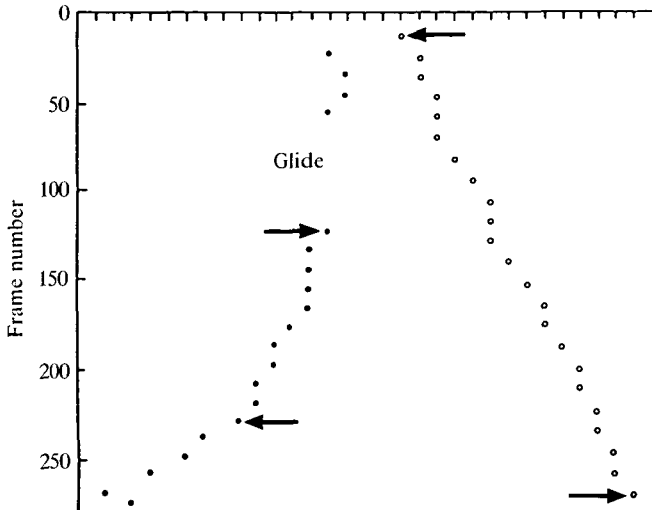


Fig. 10. An example of a plot used to compare wing beat frequencies of adjacent birds flying in formation (based on Berger, 1972). Each point is one wing beat measured from maximum wing elevation. Different symbols represent different birds. The abscissa marks are units of difference from modal frames beat^{-1} for the formation (for this case $11 \text{ frames beat}^{-1}$). Plots are started at an arbitrary abscissa value. Whenever frames for a beat equal the modal value, a point is placed directly below the previous point. A point is placed n abscissa units to the right or left of the previous point if frames beat^{-1} exceed or are less than the modal value by n frames, respectively. Wing beat frequencies were compared when slopes were uniform (between arrows for this case) over at least 10 wing beats.

Table 1. *Wing beats s^{-1} for adjacent pelicans measured over periods when both birds were flapping at uniform rates*

Forward bird	Trailing bird	Difference
3.28	2.82	0.46
3.12	2.98	0.14
2.95	2.84	0.11
2.76	2.87	0.11
2.87	3.06	0.19
2.91	2.95	0.04
3.12	3.07	0.05
2.95	3.11	0.16
3.11	3.11	0.00

Nielsen, 1974), and gliding in ground effect reduces glide angle and sink velocity so that glide time is prolonged and gliding can occur at lower minimum drag velocities (Withers & Timko, 1977; Blake, 1983). Savings for pelicans are less than for black skimmers which fly much closer to the water (1–8 cm) and have a shorter span (76 cm) (Withers & Timko, 1977); nevertheless, induced power savings of 49% should have a dramatic impact on reducing costs for flight. Other species with relatively long wing spans, such as herons and egrets, are also likely to achieve appreciable benefits from ground effect.

The pelicans differed in their formation flight positioning. There was little to suggest that they were sensitive to the location of a particular position yielding high savings. Only six birds (25%) were positioned near an optimum WTS of -22 cm. Even if the optimum is shifted to -54 cm, to account for extreme inboard horizontal vortex position variation during flapping (based on measurements from Fig. 5), there were still only six birds with 'appropriate' positions. This could be accounted for by chance, since a uniform distribution across the range of average WTS values would give six birds over the spacing intervals from -75 to 24 cm, and seven birds had average WTS values in these intervals (Fig. 8). There was a relatively narrow range of variation in vertical displacement for birds flying out of ground effect, but this would have little consequence for birds with extreme WTS values. Some individuals had average WTS values at extreme overlap where induced power savings should be negative (Fig. 7) (Higdon & Corrsin, 1978). There was no evidence of shifts of position between gliding and flapping flight, and only one individual appeared to be close to an appropriate position and also had a wing beat frequency similar enough to the bird ahead so that tracking vertical variation in a trailing vortex position might have been possible.

How do brown pelicans compare with other species which fly in formation? The positioning of two other species has been studied in detail: white pelicans and Canada geese. White pelicans were filmed, and the frame corresponding to the perpendicular view was used to reconstruct the geometry as seen directly overhead (O'Malley & Evans, 1982; see Gould & Heppner, 1974 for methods). Data were given for mean interbird distances (distances along a V leg between adjacent birds) in units of pelican lengths together with formation angles for 28 formations. I calculated average WTS for each of the formations, assuming a flying white pelican has a length of 1.0 m (white pelicans with outstretched necks measure 1.4–1.8 m, O'Malley & Evans, 1982), and a maximum wing span of 274 cm. The frequency distribution for formation average WTS shows the positive skew expected if birds were to cluster near a particular position (such as -30 cm if $b = 274$ cm) and to avoid extreme overlap of WTS (Fig. 11). Although much information is lost in averaging over entire formations, it appears that in some formations white pelicans may have maintained WTS close to values yielding relatively high savings in induced drag (Fig. 11).

More detailed information is available for Canada geese which were filmed and had their positions reconstructed to account for perspective distortion (Hainsworth, 1987). 451 WTS values for 55 geese were compared with the 286 WTS values for the

present study. Since wing spans differ considerably (150 *vs* 210 cm), the spacing index

$$R' = b' / (b' + s')$$

was calculated, where $b' = \frac{1}{4}\pi b$, and s' is the distance from a wing tip at maximum span to the centre of a trailing wing tip vortex (e.g. for geese $s' = s + 16$ cm; for brown pelicans $s' = s + 22$ cm). Canada geese show relative precision in positioning with 47% of values clustered near $R' = 1.0$ compared with only 21% for brown pelicans (Fig. 12). Also, there is a much greater range of variation for brown pelicans as expected from their distribution of average WTS (Fig. 8).

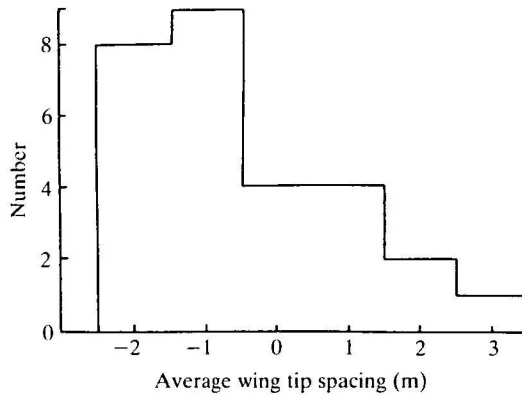


Fig. 11. Frequency distribution of average wing tip spacing for 28 formations of white pelicans from data given by O'Malley & Evans (1982). Calculations assume the length of a flying white pelican is 1.0 m and maximum wing span is 274 cm.

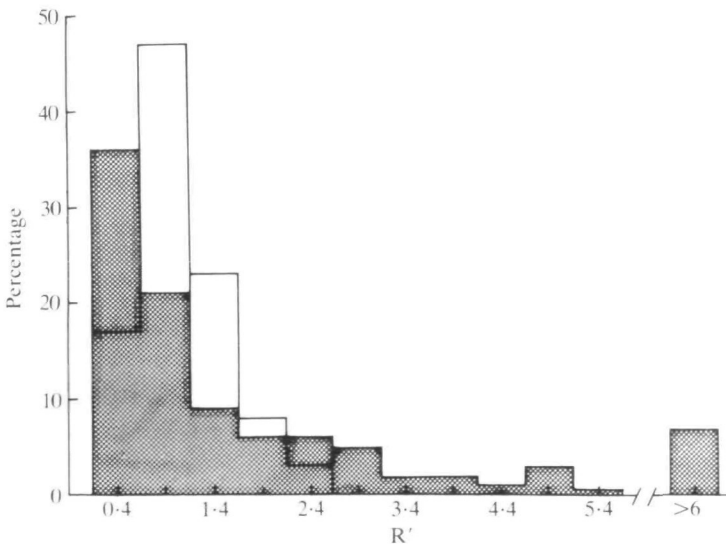


Fig. 12. Frequency distributions of R' (see text) for brown pelicans (shaded) and Canada geese (open). Data for Canada geese are from Hainsworth (1987).

Why is formation flight in brown pelicans imprecise? Interaction of trailing vortices with a surface may produce complex and unpredictable flow fields (vortex rebound, secondary vortices, unsteady separation of boundary layers, Didden & Ho, 1985; Spedding, 1987*b*) which may modify savings compared with predictions for formation flight out of ground effect (Fig. 2). Imprecision in positioning for brown pelicans flying out of ground effect may be caused by difficulty in maintaining position under windy conditions.

It is clear that formation flight need not always provide optimum benefits for locomotion. Also, since ground effects may prevent benefits from formation flight, the birds may face a choice of which mechanism to use when it is calm. The choice to fly in ground effect may be based on predictability of saving from this behaviour, since the same saving could be achieved only with precise optimum positioning in formation (Figs 1, 2). The choice may thus be similar to other cases where locomotion performance depends on relative benefits of alternative mechanisms, such as schooling in fish for energetic benefit compared with predator avoidance (Abrahams & Colgan, 1985), porpoising in penguins for energy conservation compared with respiratory ventilation (Hui, 1987) and selection of speeds based on performance criteria (Pyke, 1981).

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