# PITCHING EQUILIBRIUM, WING SPAN AND TAIL SPAN IN A GLIDING HARRIS' HAWK, *PARABUTEO UNICINCTUS*

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## Summary

1. The centre of area of the wings of a Harris' hawk gliding freely in a wind tunnel moved forward 0.09 wing chord lengths when the hawk increased its wing span from 0.68 to 1.07 m. The movement of the centre of area probably produces a positive pitching moment that, if unopposed, would cause the bird's head to rise. The tail remained folded until wing span reached 87 % of maximum and then began to spread. This behaviour is also typical of gliding birds in nature, which spread their tails when the wings are near maximum span. Tail spreading probably produces a negative pitching moment that compensates for the forward movement of the wings at maximum span.

2. As the tail spread, its centre of area moved backwards. This movement, together with the increase in tail area, can keep the centre of area of the combined wings and tail from moving forward, even at maximum wing span.

3. The tail can generate an estimated 10 % of the hawk's total lift at maximum wing span and 5 % or less at shorter wing spans.

4. I moved the centre of area of the hawk's wings forward experimentally by clipping 76 mm from primary feathers 6–10 and 38 mm from primary feather 5. The effect of this operation on the hawk's behaviour indicated that the forward movement of the centre of area of the wings caused a positive pitching moment. The hawk pitched up more in flight. It held its wings at shorter than normal spans, which partially compensated for the effects of clipping by moving the centre of area of the wings backwards. It also spread its tail at shorter than normal spans, which would compensate for an increase in the pitching moment of the wings.

## Introduction

Gliding birds typically change their wing spans while flying, both in nature and in wind tunnels (Pennycuick, 1968; Tucker and Parrott, 1970; Parrott, 1970; Tucker and Heine, 1990). This behaviour theoretically minimizes drag (Tucker, 1987), but it may also change the pitching equilibrium of the bird. The wings appear to swing forward as the wing span increases (Hankin, 1913). If the centre of pressure for the aerodynamic force on the wings also moves forward, an increase

in wing span would cause the head of the bird to pitch up unless some compensatory change occurred.

This study investigates the pitching equilibrium of a Harris' hawk (*Parabuteo unicinctus*) gliding freely with different wing spans in a wind tunnel. The hawk chose its wing span, although I experimentally changed its wings by clipping the tips off some of the primary wing feathers.

## Materials and methods

### Nomenclature

This study describes equilibrium gliding, during which the acceleration of both the bird and the air through which it glides is zero. The bird is symmetrical around a vertical, mid-sagittal plane, and the gravitational and aerodynamic forces on the bird are also symmetrical around this plane. I shall describe the wings and tail relative to an *xy* plane, perpendicular to the vertical plane of symmetry. The *x* axis is in the vertical plane and in the direction of flight through the air. The *y* axis is parallel to a line that runs from wing tip to wing tip. A *z* axis is perpendicular to the *xy* plane. The origin of these axes is defined in the next paragraph.

Wing or tail projections (Fig. 1) are projections on the *xy* plane of the wing or tail perimeters, including the indentations between feathers. The wing projection
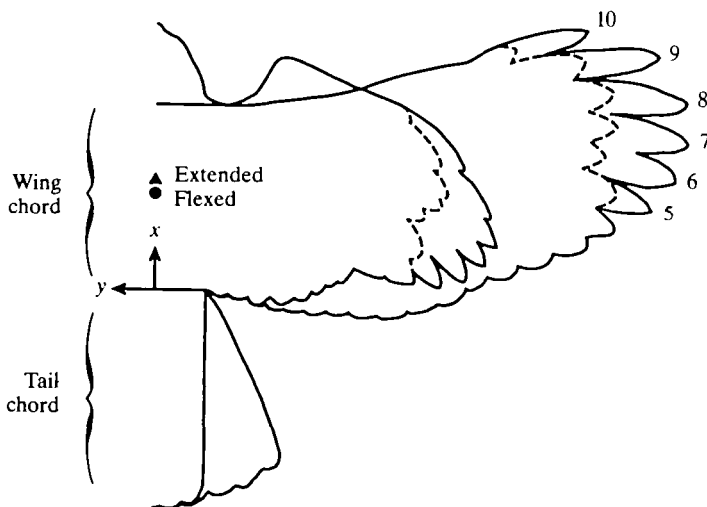


Fig. 1. Tracings of photographs of a Harris' hawk gliding with wings in the extended and flexed positions. The dashed lines outline the traced feathers after clipping. The arrows show the *x* and *y* axes, and the numerals show the numbering system for the primary feathers. The leading and trailing edge lines are the horizontal lines that connect the wing and tail projections across the body. The distance between them along the *x* axis is the wing chord (0.195 m). The triangle and the circle show the centres of area of the extended and flexed wings, respectively.

crosses the body at leading and trailing edge lines, and the tail projection crosses the body at the trailing edge line. These lines connect the points where the leading edges of the wings are most posterior near the body (Fig. 1) and again where the trailing edges meet the body. The origin of the $x$ and $y$ axes is the point where the trailing edge line crosses the $x$ axis.

I use the terms 'wing chord' and 'tail chord' to describe constant lengths associated with the wings and tail. In aerodynamic usage, 'chord' refers to the length of a structure in the direction of air flow, and this length may change in space and time. For example, the chord of the hawk wings in this study varies along the $y$ axis and, at a given $y$ value, varies as the hawk changes its wing span. However, the chord does not change with wing span at the body midline where $y=0$, and the term 'wing chord' refers to this chord. The wing chord is the length of a line – the chord line – that runs from the origin of the axes to the point where the leading edge line crosses the $x$ axis. The tail chord is similarly defined as the length of the chord line from the origin to the tip of the tail on the $x$ axis. The tail chord would be called the tail length in ordinary usage.

Several other quantities have similar definitions for both the wings and tail. Span is the maximum width of the structure, measured parallel to the $y$ axis. Area is the area enclosed by the projection of the structure. Aspect ratio is the ratio of span squared to area. Angle of attack is the angle in the vertical plane between the chord line and the $x$ axis.

I use conventional aerodynamic quantities that are described in aerodynamic texts such as von Mises (1959) or in the biological literature (for example, Vogel, 1981; Tucker, 1987; Pennycuick, 1989; Norberg, 1990). The aerodynamic force on the bird equals the bird's weight but is in the opposite direction. Drag is the component of the aerodynamic force that is parallel to the $x$ axis. Lift ($L$) is the component that is perpendicular to drag. Lift is given by:

$$L = mg\cos\theta, \tag{1}$$

where $m$ is body mass, $g$ is gravitational acceleration and $\theta$ is the glide angle – the angle between horizontal and the $x$ axis. Lift is essentially equal to body weight ($mg$), since $\theta$ is less than $10°$ and $\cos\theta$ is between 0.985 and 1 for raptors gliding at minimum glide angles.

The lift coefficient ($C_L$) of the wings or tail is given by:

$$C_L = L/qS, \tag{2}$$

where $L$ and $S$ are the lift and area of the wings or tail, and $q$ is the dynamic pressure:

$$q = 0.5\rho V^2. \tag{3}$$

The density of air is $\rho$ and $V$ is the speed at which the bird moves through the air.

## Centres

For some purposes, forces that are distributed over the surface or the volume of

a structure can be replaced with a single force that acts at a centre. Most physics texts describe the rationale for this replacement. This study uses three centres. The centre of pressure of the wings or tail is the point of application of a single aerodynamic force that replaces the varying pressures distributed over the surfaces of these structures. The centre of area of the wings or tail is the point of application of a single force that replaces a constant pressure distributed over the surface of the wing or tail projections. The centre of mass is the point of application of a single gravitational force that replaces the gravitational forces distributed over the body.

The spatial coordinates of the centre of a quantity $u$ are given by:

$$x_u = \int x \, du / u,$$
$$y_u = \int y \, du / u, \quad (4)$$
$$z_u = \int z \, du / u,$$

where

$$u = \int du, \quad (5)$$

and all integrals are taken over space. In this study, all centres are on the $x$ axis since the wings, tail and body are symmetrical around the $xz$ plane; the $z$ coordinates are zero or can be assumed to be zero without significant error.

The centre of pressure and the centre of area of a structure such as the wings or tail are not in the same position, but I assume that they are located at a constant distance from one another. This assumption equates movements in the centre of area, which this study measures, to movements in the centre of pressure. In fact, the centres of pressure and area of a wing can move independently. For example, when a rigid wing increases its angle of attack, the centre of pressure typically moves towards the leading edge (von Mises, 1959), while the centre of area does not move. Nevertheless, the assumption yields useful information about pitching equilibrium of the hawk in this study.

The centre of mass can be found from the centre of volume if the density ($\rho_B$) of the body is constant in space. In that case,

$$dm = \rho_B \, dv, \quad (6)$$

where $dm$ and $dv$ are elements of mass and volume of the body, respectively. It follows that the centre of mass ($x_m$) is given by:

$$x_m = \int x \, dv / v. \quad (7)$$

### Moments

Moments describe quantities that are distributed in space around a specified axis of rotation. This study uses first and second moments. The first moment of a quantity $u$ is:

$$\int r \, du, \quad (8)$$

where $r$ is the shortest spatial distance from the element $du$ to the axis of rotation.

The second moment is:

$$\int r^2 du. \tag{9}$$

The integrations for both moments are taken over space.

The pitching moment (described in most aerodynamics texts) is the first moment of aerodynamic force around a pitching axis that runs through the centre of mass and is parallel to the $y$ axis. The pitching moment is a torque that can be positive or negative. Positive torque causes the bird's head to rise and the tail to descend.

The pitching moment of the wings in this study is the lift on the wings multiplied by the distance between the centre of pressure of the wings and the centre of mass of the whole bird. Drag has no effect on the pitching moment because this study assumes that the centres of both pressure and mass are on the $x$ axis. The pitching moment of the tail is analogous to that of the wings. I assume that the pitching moment of the body, exclusive of the wings and tail, is negligible.

Pitching moments from gravitational forces on the bird in flight are zero because the pitching axis runs through the centre of mass. The centre of mass, however, may move as the wings swing forward or back. I assume that the movement of the centre of mass is negligible, since the mass of the wings is a small proportion of total body mass and the centre of mass of the wings is near the centre of mass for the whole bird.

When the bird is at equilibrium, the pitching moments of the wings and tail sum to zero and the angular acceleration around the pitching axis is zero. If the pitching moments do not sum to zero, the angular acceleration depends on the second moment of mass around the pitching axis – the moment of inertia ($I$). For example, the wings of a bird gliding at equilibrium produce lift approximately equal to $mg$, where $m$ is body mass and $g$ is gravitational acceleration. If the centre of pressure of the wings moves relative to the pitching axis by distance $x$, an unbalanced pitching moment equal to $mgx$ arises. The resulting angular acceleration ($\dot{\omega}$) is:

$$\dot{\omega} = mgx/I. \tag{10}$$

The angular acceleration in equation 10 depends on the bird's volume ($v$) and the second moment of volume ($I_v$). Assuming constant body density ($\rho_B$),

$$I = \rho_B I_v \tag{11}$$

and

$$\dot{\omega} = vgx/I_v. \tag{12}$$

### *Harris' hawk, wind tunnel and wing clipping*

I photographed a male hawk from above as it glided freely at equilibrium at different speeds in a wind tunnel. Tucker and Heine (1990) describe the bird, the wind tunnel and the methodology in detail. The tunnel was tilted to the minimum angle at which the bird could just remain motionless when centred laterally in the tunnel and at least 0.25 m from the roof. Motionless means that the hawk's body did not move in any direction by more than 2 cm in a second. The hawk kept its feet tucked under its tail when it was motionless at the minimum angle. The hawk

had a body mass of between 0.66 and 0.68 kg during the experiments, which were completed 2 weeks prior to the bird's second annual moult.

All air speeds are calculated from measurements of dynamic pressure, using an air density of 1.23 kg m$^{-3}$, the density of air in the US Standard Atmosphere at sea level (von Mises, 1959). I calculated total aerodynamic drag (corrected for tunnel boundary effects) from the bird's weight and the tunnel angle, and determined the wing and tail shape, span and area from the photographs.

I photographed the hawk with three wing configurations: (1) with unclipped feathers (Fig. 1), (2) with 38 mm clipped from the tips of each primary feather 6–10, and (3) with 38 mm clipped from each primary 5 and an additional 38 mm clipped from each primary feather 6–10 (Fig. 1). (Harris' hawks have 10 primary feathers on each wing, numbered consecutively from 1 to 10 with 10 on the leading edge of the wing.) I tapered the clipped ends of the feathers to match the shape of the unclipped feathers. Only the results from configurations 1 and 3 are reported here. The results from configuration 2 were intermediate and support the findings of this study.

## Wing morphology

I used a planimeter to determine the wing chord, span and area of wing projections traced from photographs enlarged to approximately one-quarter life size. I determined the actual wing chord by photographing the hawk in flight as it carried a paper streamer of known length (Tucker and Heine, 1990). The streamer was attached to a paper collar around the bird's neck and trailed down the midline of the back. The actual wing chord and the wing chord measured from the projections allowed me to compute the actual dimensions of the wings from the projections.

I located the centre of area of the wings from the $xy$ coordinates (accurate to 0.25 mm on the wing projection) of approximately 300 points on the projection. The wing projections were divided into strips running parallel to the $x$ axis. Each strip was 1.5 mm wide on the projection with a length determined by the points where the strip crossed the projection. I summed the strip areas and the area moments (the strip area multiplied by the $x$ and $y$ coordinates of the centre of the strip) to find an approximate solution for equations 4 with negligible error.

I also measured the sweepback angle of the right and left eighth primary feathers on the wing projections. The tips of these feathers define the wing span (Fig. 1). The sweepback angle is the mean of the angles between the $y$ axis and the shafts of both feathers.

## Tail morphology

I measured tail chord and span on tail projections traced from photographs enlarged to approximately one-quarter life size. A mathematical model relates the tail area and centre of area to chord and span. The model represents the tail as a rectangle, two triangles and a segment of a circle (Fig. 2). The width of the
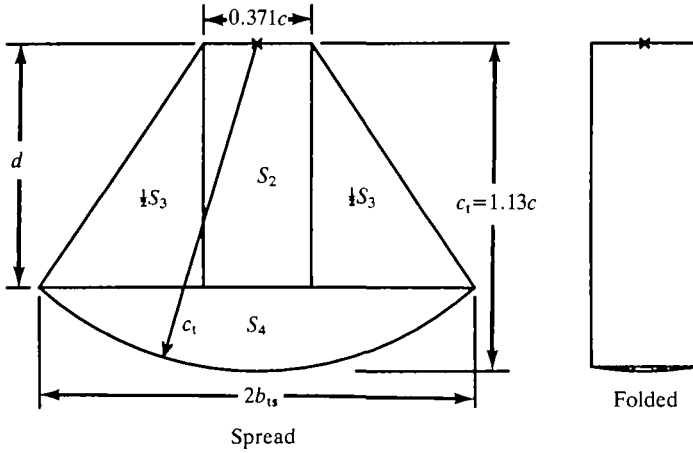
Fig. 2. The tail model, shown both folded and spread to a span of 1.5 wing chords, has four parts: a rectangle of area $S_2$, two triangles of combined area $S_3$ and a segment of a circle of area $S_4$. A cross marks the centre of the circle, which has a radius equal to the tail chord ($c_t$). The symbol $c$ refers to the wing chord. $d$, length of rectangular part of tail; $b_{ts}$, tail semi-span.

rectangle and the chord of the tail ($c_t$) are constant, but the length of the rectangle ($d$) varies with the tail semi-span ($b_{ts}$):

$$d = (c_t^2 - b_{ts}^2)^{1/2} . \tag{13}$$

The area of the circle segment is:

$$S_4 = c_t^2 \tan^{-1}(b_{ts}/d) - db_{ts} , \tag{14}$$

and the equations for areas of the triangles and the rectangle are obvious from Fig. 2.

I found the centre of area of the tail by integrating the mathematical functions that describe a rectangle, a triangle and a segment of a circle. The centres of area for these tail parts are located at:

$$x_{S_2} = -d/2 , \tag{15}$$

$$x_{S_3} = -2d/3 , \tag{16}$$

and

$$x_{S_4} = -2b_{ts}^3/(3S_4) . \tag{17}$$

The location of the centre of area of the combined wings and tail ($x_{S,T}$) is given by:

$$x_{S,T} = (\Sigma x_{S_i} S_i)/\Sigma S_i , \tag{18}$$

where $i=1, 2, 3$ or 4 and the subscript 1 indicates the wings.

### Moments of volume and inertia

I estimated the volume of the body and the first and second moments of volume from three-dimensional coordinates of 999 points on the surface of a wingless,

frozen peregrine falcon (*Falco peregrinus*) body (Tucker, 1990). The falcon and the hawk had similar body proportions and, in life, the falcon had a similar total mass (0.713 kg). A computer program reconstructed the body from the surface points and divided it into slices perpendicular to the $x$ axis and 7.93 mm thick. The volume of all the slices was $586 \times 10^{-6} \, m^3$. The program assumed that all the slices had the same density and located the centre of mass from the first moment of volume. The program then computed the second moment of volume ($6.03 \times 10^{-6} \, m^5$) around the centre of mass by approximating d$u$ in equation 9 with the volume of the slice and $r$ with the distance along the $x$ axis between the centre of mass and the centre of the slice.

This approximation underestimates the second moment of volume of the intact hawk. It does not completely account for the volume of the wingless body that is near the centre of mass, nor does it account for the volume of the wings and tail. Including these structures would not have much effect on the approximation because their volumes are relatively low and the centre of volume of the wings is near the centre of mass for the wingless body. The estimate of the second moment of volume should be correct to well within a factor of two, which is accurate enough for present purposes.

## Results

### Behaviour

The hawk with unclipped wings alternately flapped and glided in the wind tunnel as described in Tucker and Heine (1990). Clipping had a dramatic effect: the hawk started to glide but then pitched up until its body was vertical. It used its feet to fend off a collision with the roof as it was blown towards the rear of the tunnel, and it usually began to flap before crashing into the screen at the back of the test section. It then glided forward to pitch up again after a few seconds. After several minutes of this, the hawk was able to fly for about a minute without pitching up.

During periods of gliding, the clipped hawk was often at the top of the tunnel with its back against the roof or at the side of the tunnel with one wing tip touching the wall. It was reluctant to glide at any speed, and would not glide at the slowest speed it reached before clipping. At this speed, it simply landed after being launched into the air. The lift coefficient of the wings at this speed would have been 1.4, still below the maximum of 1.6 for the intact bird (Tucker and Heine, 1990).

The clipped bird went through this sequence each day when it was placed in the tunnel. The unclipped bird sometimes pitched up a few times at the beginning of a flight, but almost never did so after a minute or two.

The unclipped hawk glided in a position suitable for photography at about 1-min intervals. After clipping, the comparable interval was 3–5 min.

### Wing morphology

The wing chord was constant (0.195 m, $N=15$, s.d.$=0.0020$ m) at all spans. Figs 3–6 and Table 1 describe wing characteristics that varied with wing span.
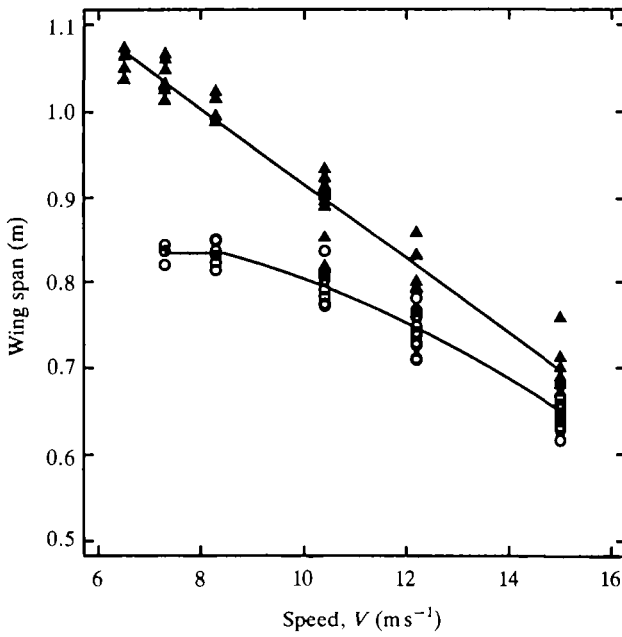
Fig. 3. Wing span at minimum glide angles at different speeds for unclipped wings (triangles) and clipped wings (circles).
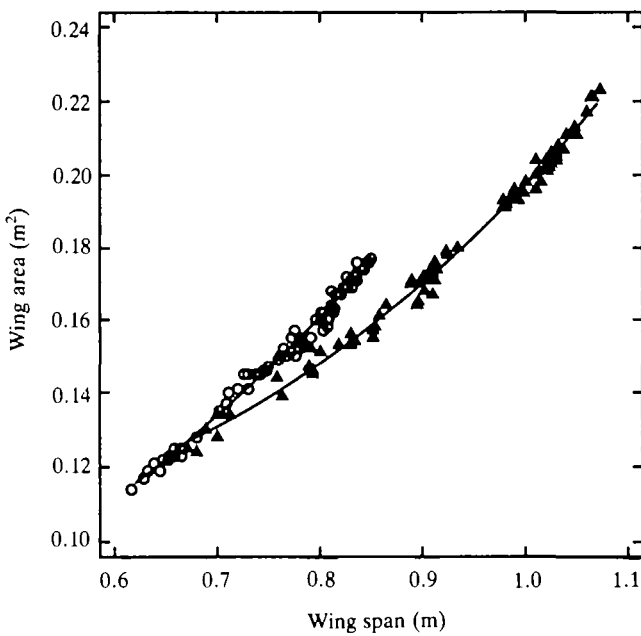


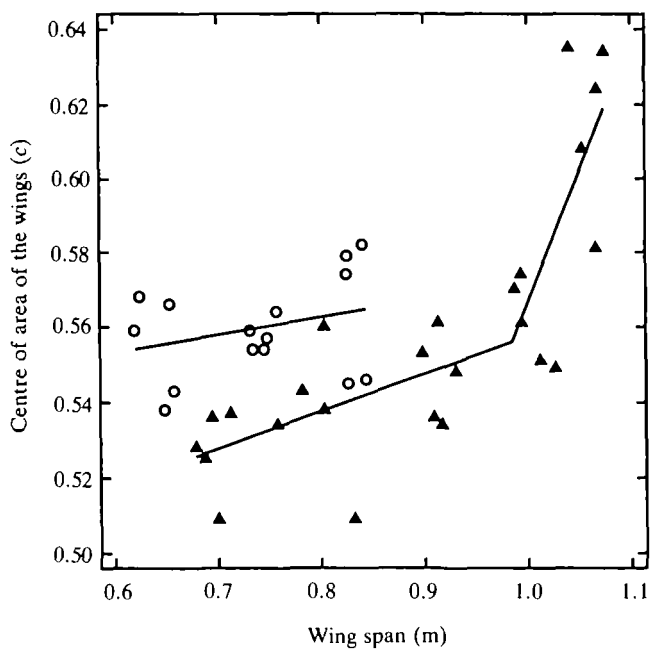Fig. 4. Wing area at different wing spans for unclipped wings (triangles) and clipped wings (circles).

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Fig. 5. Centre of area of the wings at different wing spans during flight. The vertical axis gives distance in units of wing chords (c) ahead of the trailing edge line. The triangles are data for five unclipped wing projections selected randomly at each of three speeds. The circles are similar data for clipped wings at each of four speeds. The speed ranges include the highest and lowest speeds at which the bird would fly.

Table 1. *Coefficients for wing morphology equations*

| Variable $X$ and range | Variable $Y$ and condition | Coefficients | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | $C_0$ | $C_1$ | $C_2$ | $s_{Y.X}$ | $N$ |
| Wing span (m) | Wing area ($m^2$) | | | | | |
| 0.67–1.07 | (unclipped) | 0.1530 | −0.2087 | 0.2530 | 0.00234 | 75 |
| 0.62–0.85 | (clipped) | 0.0760 | −0.0800 | 0.2325 | 0.00197 | 75 |
| Speed ($m s^{-1}$) | Wing span (m) | | | | | |
| 6.5–15.0 | (unclipped) | 1.354 | −0.0438 | 0 | 0.0250 | 51 |
| 7.3–8.3 | (clipped) | 0.834 | 0 | 0 | 0.0119 | 10 |
| 8.3–15.0 | (clipped) | 0.851 | 0.0126 | −0.0017 | 0.0184 | 44 |
| Wing span (m) | Sweepback angle (degrees) | | | | | |
| 0.68–1.06 | (unclipped) | 105.7 | −86.9 | 0 | 2.80 | 25 |
| Wing span (m) | Centre of area (chord units) | | | | | |
| 0.68–1.03 | (unclipped) | 0.459 | 0.099 | 0 | 0.0136 | 20 |
| 0.99–1.07 | (unclipped) | −0.140 | 0.706 | 0 | 0.0255 | 10 |
| 0.62–0.84 | (clipped) | 0.525 | 0.047 | 0 | 0.0131 | 15 |

Equations are descriptive, of the form $Y=C_0+C_1X+C_2X^2$ and fitted by least-squares regression.

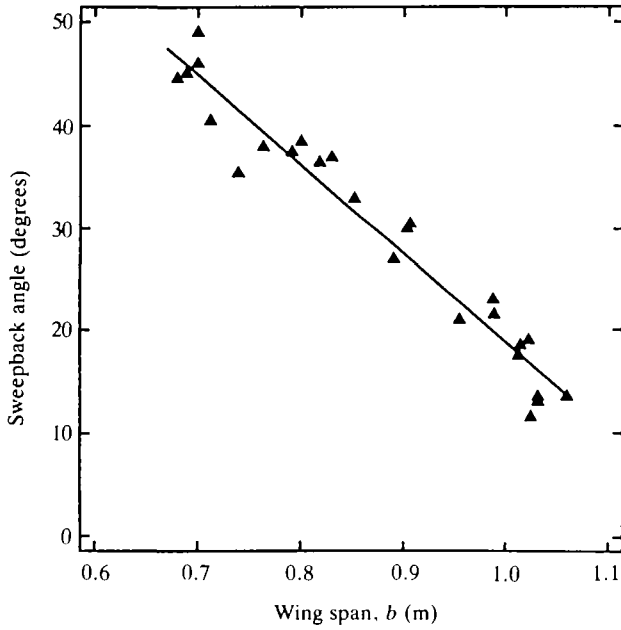$s_{Y.X}$ is the standard deviation of $Y$ around the fitted curve.

Fig. 6. The sweepback angle of the eighth, unclipped primary feathers at different wing spans. The line is fitted by least-squares regression.

### Tail morphology

Tail span, expressed in wing chords, varied with wing span (Fig. 7). Two parametric equations, four constants and the variable $T$ describe the circular curves in Fig. 7 on horizontal $(X)$ and vertical $(Y)$ axes:

$$X = X_0 + R_X \cos T,$$
$$Y = Y_0 + R_Y \sin T, \tag{19}$$

where $T$ varies from 270 to 360°. The constants also describe the lines: the $Y$ value for the horizontal line is $Y_0 - R_Y$, and the $X$ value for a vertical line is $X_0 + R_X$. For unclipped wings, $X_0 = 0.934$, $Y_0 = 0.647$, $R_X = 0.100$ and $R_Y = 0.278$. The constants for clipped wings are the same as those for unclipped wings, except that $X_0 = 0.734$.

Figs 8 and 9 show characteristics of the tail model that varied with the tail span. These curves use the wing chord $(c)$ as the unit of length. The tail chord was $1.13c$ and the span of the folded tail was $0.371c$.

### Discussion

#### Unclipped wings

*Pitching moments at equilibrium*

The pitching moment of an aircraft with rigid wings can be adjusted by moving the wings, and hence the centre of pressure of the wings, forward or back relative
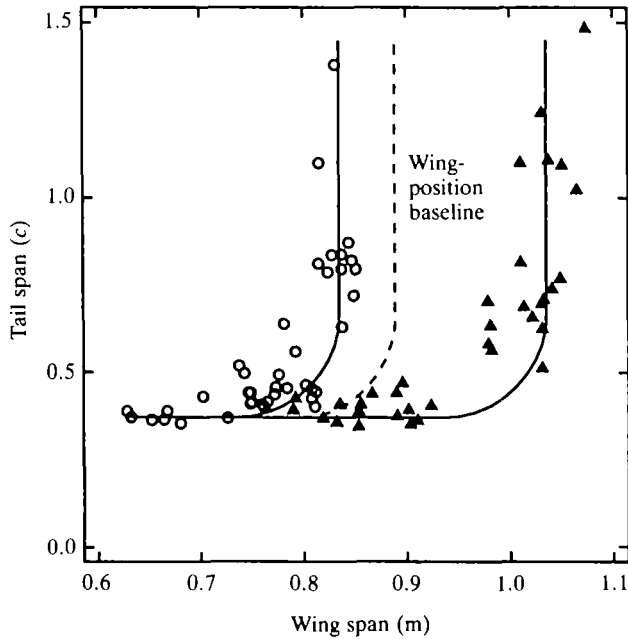
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Fig. 7. Tail span (in units of wing chord, $c$) at different wing spans for unclipped wings (triangles) and clipped wings (circles). The solid lines are fitted by eye to the data. The dashed curve is the wing-position baseline. It describes the tail spans that would result if the tail span were set by the position of the wing bones whether the wings were clipped or not.

to the centre of mass of the aircraft. The position of the wings in a conventional aircraft is fixed during construction, but gliding birds may swing their wings forward or back during flight. In fact, birds are thought to use this method to control pitch (Pennycuick, 1975). The present study shows that the variable wing span of birds is also involved in pitch control because the forward or backward position of the wings depends on wing span.

The observations in the wind tunnel suggest that the wings and tail of the gliding Harris' hawk form a variable-area, two-part lifting system that keeps the hawk in pitching equilibrium as its wing span changes. As the wing span increases, the centre of area of the wings moves forward (Fig. 5), and the pitching moment of the wings increases. The tail remains folded until wing span reaches 0.93 m (87 % of maximum span) and then it begins to spread (Fig. 7). At about this span, the change in the centre of area of the wings with a change in wing span increases (Fig. 5). Tail spreading probably generates negative pitching moments that compensate for the increased pitching moment as the wing span increases.

The centre of area for the combined wings and tail moves forward as wing span increases (Fig. 10). However, the tail area can increase enough to keep the combined centre of area at a constant position, even at maximum wing span.

It may not be obvious how the combined centre of area in Fig. 10 can move forward more than the wing centre of area. Equation 18 explains this phenom-
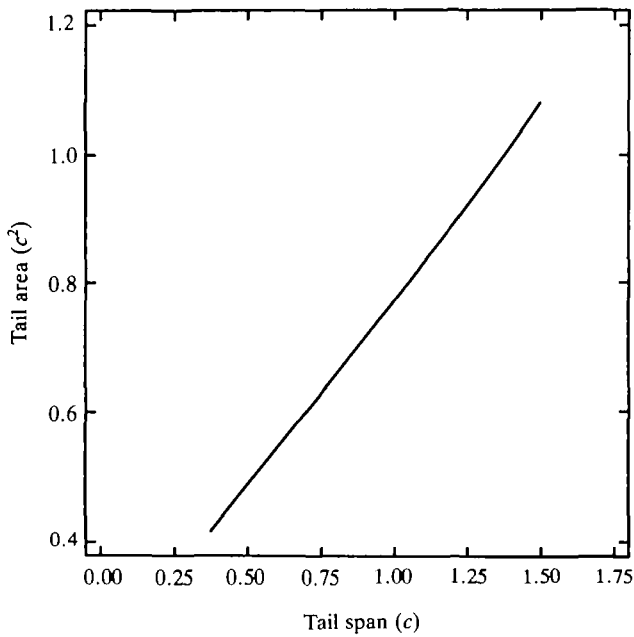
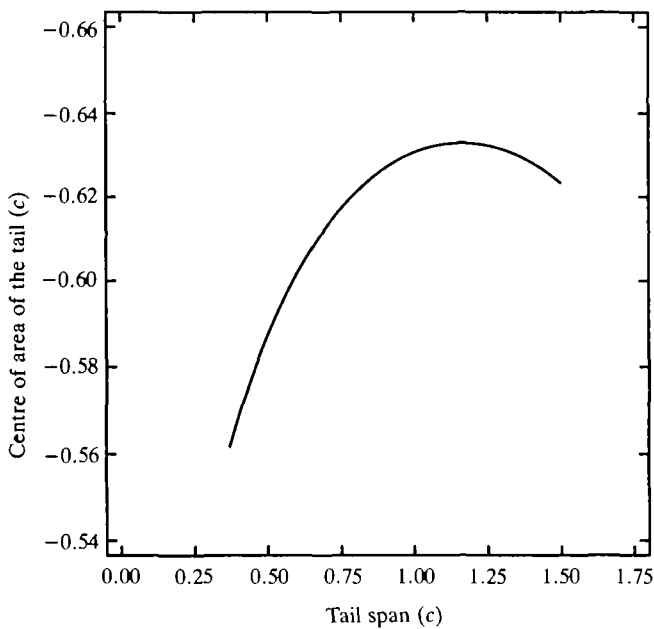Fig. 8. Area of the tail model at different tail spans. The unit of length is the wing chord ($c$).



Fig. 9. Centre of area of the tail model at different tail spans (in units of wing chord, $c$). The vertical axis gives the distance in wing chords behind the trailing edge line.
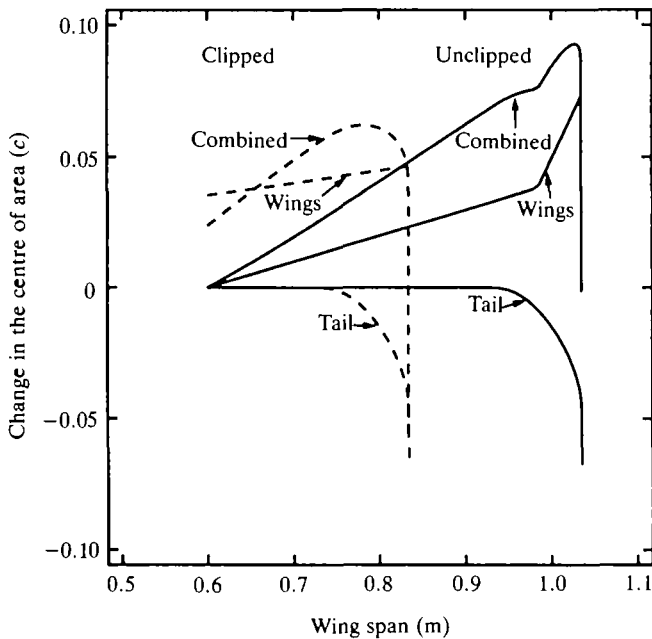
Fig. 10. Changes in the centres of area of the wings, tail and combined wings and tail at different wing spans. The vertical axis shows the change in each centre (in units of wing chord) relative to the corresponding centre in the hawk with unclipped wings and a wing span of 0.6 m. Positive and negative changes indicate forward and backward directions, respectively. The solid lines represent the hawk with unclipped wings, and the dashed lines represent the hawk with clipped wings.

enon, and an intuitive example occurs when the wing area increases with no change in the wing centre of area. Because the wing centre of area is ahead of the combined centre of area, the latter moves forward even though the wing centre of area does not.

Tail lift contributes perhaps 10 % of the total lift at maximum wing span and 5 % or less at shorter wing spans. I calculated these proportions from the relative areas and lift coefficients of the wings and tail. The tail area ($S_t$) is about 10 % of the wing area ($S_1$) at most wing spans but increases to 20 % when the tail spreads to $1.5c$ (Fig. 11). The wings have relatively high lift coefficients ($C_{L_w}$) – from 0.6 at $12\,\mathrm{m\,s^{-1}}$ to 1.6 for fully spread wings at $6\,\mathrm{m\,s^{-1}}$ (Tucker and Heine, 1990) – because of their cambered aerofoils and aspect ratio of 5.1 at maximum span. The tail has relatively low lift coefficients ($C_{L_t}$) because it has a flat aerofoil and its aspect ratio is only 2.1 at a tail span of $1.5c$. When folded, the aspect ratio of the tail is 0.3. Flat plates with these aspect ratios have lift coefficients of 0.5–1.0, respectively, at an angle of attack of 20° (Carter, 1940). I estimated by eye that the angle of attack of the tail was always less than 20° in this study.

The ratio of tail lift to wing lift at a particular speed is given by:

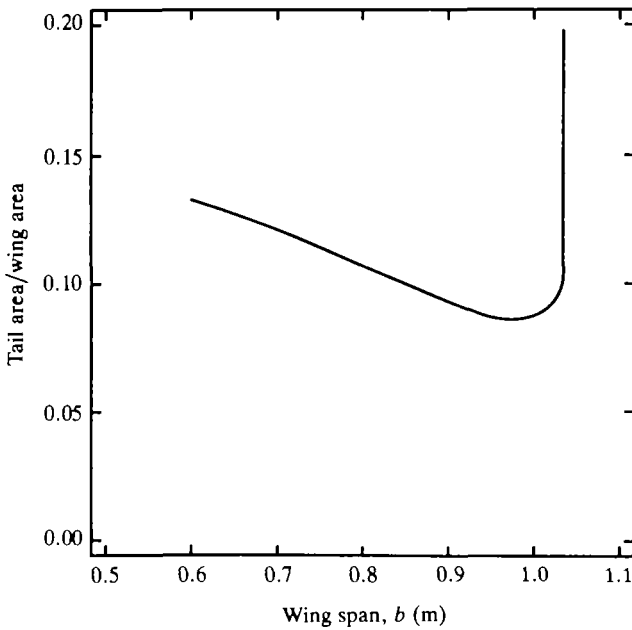$$L_t/L_w = S_t C_{L_t}/S_1 C_{L_w}. \tag{20}$$

Fig. 11. Tail area as a fraction of the unclipped wing area at different wing spans.

I used a value of 0.5 for $C_{L_t}/C_{L_w}$ to calculate the ratio of tail lift to wing lift in the previous paragraph.

### Non-equilibrium pitching moments

*Rate of pitch.* The bird would pitch upward if the tail did not compensate for the forward movement of the wings with increasing wing span. As a first approximation, the angular acceleration of the resulting pitch would be substantial: $1094° \, s^{-2}$, which would cause a pitch of $137°$ in $0.5 \, s$. To compute these values, I used equation 12 and a value of $97.2 \, m^{-2}$ for the ratio of volume to the second moment of volume. I assumed that the centre of area of the wings moved forward by $0.02 \, m$ (0.103 chord units) and that the centre of pressure moved forward by the same distance as wing span increased from minimum to maximum.

*Control of pitching moment.* The wings and tail both spread in a manner that affects the pitching moment in two complementary ways. The pitching moment is the product of two factors: lift acting at a centre of pressure and a moment arm – the distance between the centre of pressure and the centre of mass. Both factors increase when the wings or tail spread because spreading not only increases area but increases it in a way that moves the centre of pressure away from the centre of mass.

For example, as the tail spreads, tail lift increases at a given speed and lift coefficient because lift is proportional to tail area under these conditions. The moment arm increases because the tail spreads more at its distal end. As a result, the centre of area of the tail (and by assumption, the centre of pressure) moves

backwards (Fig. 9). Both the change in area and the change in the centre of pressure make the pitching moment of the tail more negative. Similar relationships hold as the wings spread and produce positive pitching moments.

Changes in the angle of attack of the wing tips may have an important role in pitch control, particularly when the wings are at maximum span or are strongly flexed. In the former case, the tips are ahead of the centre of area of the whole wing, and in the latter case they are behind it (Fig. 1). In either case, the tips could have a large moment arm and a large effect on the pitching moment. An increase in lift at the tips would increase the pitching moment at maximum span but decrease it at short spans.

The vertical position of the wings relative to the centre of mass can also affect the pitching moment. This study assumes that the vertical displacement of the wings is negligible, but some birds hold their wings with large positive or negative dihedral. In such cases, the pitching moment of the wings may be positive, negative or zero, depending on where the centre of pressure is relative to a line in the $xz$ plane that passes through the centre of mass. This line tilts backwards from the $z$ axis at an angle ($\gamma$) with the $x$ axis that depends on the lift to drag ($D$) ratio of the wings:

$$\gamma = \tan^{-1} L/D. \tag{21}$$

A bird could hold its wings above or below the $xy$ plane without generating a pitching moment if the centre of pressure of the wings were on the line through the centre of mass. However, if the bird held its wings so that the centre of pressure were ahead of or behind the line, the wings would have positive or negative pitching moments, respectively.

*Observations in nature*

After noticing that the tail of the Harris' hawk in the wind tunnel began to spread only when the wings approached maximum span, I began to look for this behaviour in birds soaring in nature. I watched numerous Turkey vultures (*Cathartes aura*) and red-tailed hawks (*Buteo jamaicensis*) gliding near Duke University. They invariably spread their tails when gliding with fully spread wings, typically while circling, and folded them when gliding with even slightly flexed wings.

Artwork and photographs in field guides also indicate that raptors spread their tails when they spread their wings to maximum span. For example, drawings in Dunne *et al.* (1988) of all types of North American diurnal raptors in flight show the birds with spread tails only when the wings are fully spread. These authors describe (page 5) '...the very picture of a buteo, wings fully extended, tail fanned. But when the same bird glides,...it draws in its wings and closes its tail...' Photographs and drawings in Clark and Wheeler (1987) and in Kerlinger (1989) also show gliding birds with spread tails only when the wings are fully extended.

In fact, many authors (for example, those cited above and Raspet, 1960) distinguish two types of flight on fixed wings: soaring with fully spread wings and

gliding with flexed wings. The Harris' hawk in the wind tunnel did not have a dichotomous wing span – it glided with a continuous range of spans. Tail spreading, however, could be used to distinguish two types of flight, because the tail spread abruptly as wing span approached maximum (Fig. 7).

### Clipped wings

Clipping moves the centre of area of the wings forward at wing spans less than maximum because it removes an area behind the centre of area of the unclipped wings (Fig. 1). If the assumption that the centre of pressure moves with the centre of area is correct, then clipping should increase the pitching moment of the wings and should change four aspects of the hawk's behaviour. (1) The clipped hawk should pitch upwards more than the unclipped hawk. (2) The clipped hawk should decrease its wing span at a given speed to move the centre of pressure backwards and compensate for the forward movement caused by clipping. (3) The clipped hawk should increase its tail span at smaller wing spans than the unclipped bird to compensate for the forward movement of the wing centre of pressure caused by clipping. (4) The hawk should spread its tail when the centre of area of the combined wings and tail moves forward a given distance, whether the wings are clipped or unclipped.

In fact, clipping did alter the hawk's behaviour as predicted in items 1–4. Evidently, clipping changed the pitching moment of the wings, and the hawk restored equilibrium by adjusting its wings and tail. I shall discuss items 2–4 in detail below.

### Wing span

The question of whether the clipped hawk reduced its wing span at a given speed introduces another question. From what baseline of span *versus* speed should span reduction be measured? Clipping alone reduces the span of wings held in a fixed position. I shall consider reductions in wing span from two baselines that depend on what cues the hawk attends to when adjusting its wing span.

The *speed baseline* results from the assumption that the hawk adjusts the position of its wing bones at a given air speed to the same position, whether the wings are clipped or not. With this assumption, the span ($b_c$) of the clipped wings is less than the span ($b$) of the unclipped wings:

$$b_c = b - 2f\cos\beta, \tag{22}$$

where $f$ is the length clipped off each eighth primary feather and $\beta$ is the angle at which the eighth primaries are swept back from the $y$ axis at a given span for the unclipped wings (Fig. 6). (The tips of the eighth primaries define the wing span.) I computed the speed baseline (Fig. 12) by subtracting $2f\cos\beta$ from the curve for unclipped wings in Fig. 3.

The *drag baseline* results from the assumption that the hawk adjusts its wing span to minimize the sum of induced drag and profile drag. This baseline results in greater wing spans at most speeds than the speed-sensitive baseline because the
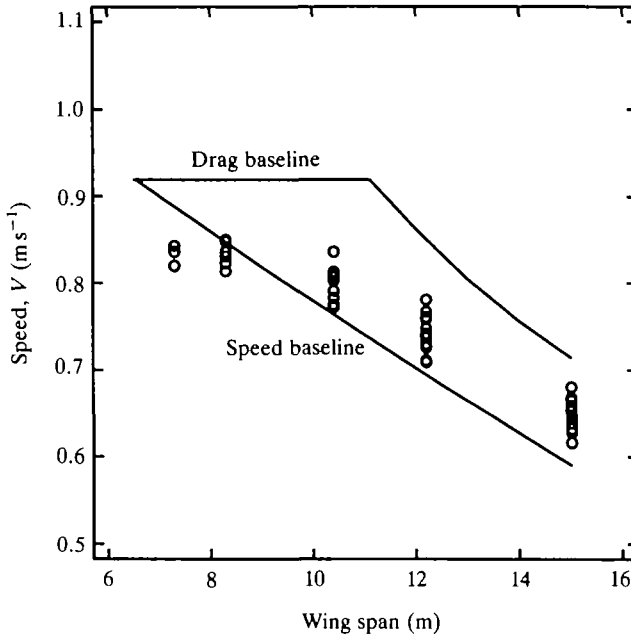
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Fig. 12. The speed baseline and drag baseline for wing span at different speeds. The circles are data for clipped wings.

hawk extends its wings, if possible, to compensate for the reduction in span (and increase in induced drag) from the clipped feathers. Fig. 12 shows the drag baseline.

I calculated the position of the drag baseline for the Harris' hawk by the method described in Tucker (1987). I determined the total drag of the hawk with clipped wings from the tilt of the wind tunnel, used a parasite drag coefficient of 0.18 (Tucker, 1990) to calculate parasite drag, and used an induced drag factor of 1.1 to calculate induced drag. I subtracted parasite and induced drag from total drag to obtain profile drag and then constructed a polar curve for the profile drag coefficient. I used the polar curve to calculate the drag baseline.

If the hawk were to reduce its wing span to control pitching, its wing span with clipped wings would be less than one or both of these baselines. The hawk reduced its wing span below the drag baseline at all speeds, but wing span was above the speed baseline except at the slowest speeds (Fig. 12). These results support the assumption that the centre of pressure moves forward with the centre of area as the wing span increases. They also indicate that the hawk adjusts its wing span at each speed to control both drag and pitching moments rather than simply setting its wing bones to a fixed position at each speed.

*Tail span*

Just as for wing span, the question of whether the clipped hawk increased its tail span at smaller wing spans than the unclipped hawk introduces another question.

From what baseline of tail span *versus* wing span should the smaller wing span be measured? Clipping alone reduces the span of wings held in a fixed position. I shall consider reductions in wing span from a baseline that shows, for a given tail span of the unclipped bird, what the wing span would be if the wings were clipped with no movement of the wing bones. This *wing-position baseline* describes the tail span of a bird with clipped wings that sets its tail span according to the wing-bone positions, whether the wings are clipped or not. Fig. 7 shows the wing-position baseline.

The results in Fig. 7 support the assumption that the centre of pressure of the wings moves with the centre of area: the tail of the clipped bird spreads at smaller wing spans than those on the wing-position baseline. Evidently, the hawk spreads its tail to compensate for the positive pitching moment caused by clipping the wings rather than spreading its tail according to the wing-bone positions.

*Centre of area of the combined wings and tail*

The spreading of the tail that accompanied the forward movement of the centre of area of the combined wings and tail supports the assumption that the centre of pressure of the wings moves with the centre of area. The tail span of both the clipped and unclipped hawk increased when the centre of area of the combined wings and tail moved forward by about the same amount – $0.056c$ for the clipped wings and $0.070c$ for the unclipped wings – even though these forward movements occurred at different wing spans (Fig. 10).

## List of symbols

| | |
|---|---|
| $b$ | wing span, unclipped wings |
| $b_c$ | wing span, clipped wings |
| $b_{ts}$ | tail semi-span |
| $C_L$ | lift coefficient |
| $C_{L_t}$ | lift coefficient of tail |
| $C_{L_w}$ | lift coefficient of wing |
| $c$ | wing chord, also used as a unit of length |
| $c_t$ | tail chord |
| $D$ | drag |
| $d$ | length of rectangular part of tail |
| $f$ | length clipped off the eighth primary |
| $g$ | acceleration due to gravity |
| $I$ | moment of inertia |
| $I_v$ | second moment of volume |
| $i$ | subscripts in equation 18 |
| $L$ | lift |
| $L_t$ | lift of tail |
| $L_w$ | lift of wings |
| $m$ | mass |
| $q$ | dynamic pressure |

| | |
|---|---|
| $R_X, R_Y$ | constants in equations 19 |
| $r$ | distance from axis of rotation |
| $S$ | area |
| $S_1$ | wing area |
| $S_2, S_3, S_4$ | parts of tail area |
| $S_t$ | tail area |
| $T$ | variable in equations 19 |
| $u$ | an unspecified quantity with a centre |
| $V$ | air speed |
| $v$ | volume |
| $X, Y$ | quantities identified in Table 1 |
| $X_0, Y_0$ | constants in equations 19 |
| $x, y, z$ | spatial coordinates |
| $x_m$ | centre of mass |
| $x_{S_1}$ | location of wing centre of area |
| $x_{S_2}, x_{S_3}, x_{S_4}$ | locations of centres of area of tail parts |
| $x_{S,T}$ | location of centre of area of combined wings and tail |
| $x_u, y_u, z_u$ | spatial coordinates of centres |
| $\beta$ | sweepback angle of eighth primary feathers |
| $\gamma$ | angle in equation 21 |
| $\dot{\omega}$ | angular acceleration |
| $\rho$ | air density |
| $\rho_B$ | body density |
| $\theta$ | glide angle |

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