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Tail effects on yaw stability in birds

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Abstract

Bird tails, which are an aerodynamic surface in the horizontal plane, are treated with regard to their effects on yaw stability. Reference is made to wings of very small aspect ratio similar to the values of bird tails in order to identify features which are significant for the aerodynamic yawing moment characteristics due to sideslip. It is shown that there are yawing moments of considerable magnitude for this aspect ratio region. Furthermore, the lift coefficient, which also exerts an influence, is included in the treatment of yaw stability. To show more concretely the addressed effects for birds, the yawing moment characteristics of the wing–tail combination of a pigeon, which is considered as a representative example, are treated in detail. For this purpose, a sophisticated aerodynamic method capable to deal with the mutual flow interactions between the tail and the wing is used to compute results of high precision. The yawing moment characteristics of the pigeon wing–tail combination with respect to the sideslip angle and the lift coefficient are determined, with emphasis placed on the contribution of the tail. It is shown that there is a significant contribution of the tail to yaw stability. The findings of this paper on the contribution of the tail to the yawing moment characteristics are supported by an evaluation of existing experimental data. Furthermore, the physical mechanisms are considered which are the reasons for the stabilizing role of the tail. These effects concern the contribution of the drag acting at the tail to the yawing moment. In addition, it is shown that extended legs and feet, when exposed to the airflow, can contribute to yaw stability.

Keywords: Horizontal tail; Yawing moment; Flight stability; Avian flight; Biomechanics

1. Introduction

Yaw stability, which concerns the lateral–directional motion of the birds, is an essential constituent of overall stability of flight. It is of equivalent significance as pitch stability, which is related to the longitudinal motion. For inherent yaw stability, the aerodynamic moment caused by a sideslip disturbance must be such as to tend to restore the bird to the symmetric flight condition. Otherwise, there would be yaw instability showing an increase of the sideslip disturbance.

In recent papers, the stability of flight in birds is treated, with emphasis placed on the longitudinal motion (Krus, 1997; Taylor and Thomas, 2002; Thomas and Taylor, 2001). For yaw stability, considerations are given in qualitative terms. Basically, this also holds for other relevant papers concerned with research on yaw stability (e.g., Brown, 1963; Herzog, 1968; Nachtigall, 1985; Norberg, 1990; Pennycuick, 1975; Alexander, 2002).

A central issue of yaw stability in birds is how the aerodynamic moments are generated to provide a restoring capability against a disturbance in sideslip. Since birds do not have a vertical tail which would be an efficient means for achieving yaw stability, they must rely on the wing, the body and possibly the tail to produce yawing moments due to sideslip. As far as these components of the aerodynamic configuration of the bird are concerned, recent research shows that the wing plays a most important role for yaw stability (Sachs, 2005a, b; Sachs and Moelyadi, 2006). It turns out that sweep in the wing or in its slotted tips is a feature which efficiently augments the ability to generate stabilizing yawing moments.

An interesting aspect concerning yaw stability is the role of the tail of birds. Since the tail of birds is basically an aerodynamic surface in the horizontal plane, it is generally

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considered to contribute only to forces and moments of the longitudinal motion (Balmford et al., 1993; Brümmer, 1998; Buchanan and Evans, 2000; Evans, 2003, 2004; Evans et al., 2001; Evans and Thomas, 1992; Fitzpatrick, 1999; Hedenström, 2002; Hummel, 1991, 1992; Lindhe Norberg, 2004; Maybury and Rayner, 2001, Maybury et al., 2001; Matyjasiak et al., 2004; Norberg, 1990, 1995; Pennycuick, 1968; Thomas, 1993, 1996a, b, 1997; Thomas and Balmford, 1995, 1975; Tubaro 2003; Tucker, 1992). There are effects of the tail on the lift, the drag and the pitching moment, yielding an influence on flight performance as well as on longitudinal stability, control and balance. With respect to yaw stability and related aerodynamic moments, knowledge is lacking as to whether the tail—unless changed into a laterally/directionally effective form or attitude—exerts an influence. A laterally/directionally effective form is due to twisting. When twisted, the tail can generate yawing moments (Hummel, 1991, 1992; Warrick et al., 2002). Twisting the tail means that it is turned around the longitudinal axis so that it is no longer an aerodynamic surface strictly in the horizontal plane, but has a component also in the vertical plane. Another laterally/directionally effective form relates to turning where the tail is considered to function as a rudder (Thomas, 1997).

It is the purpose of this paper to show that tails of birds can generate yawing moments in case of a sideslip disturbance and, thus, contribute to stability in the related axis. This holds for tails strictly in the horizontal plane without twisting such that there is no component in the vertical plane. It will be shown that the horizontal tail basically provides a positive contribution to yaw stability, which can be of significant magnitude when compared with the wing.

2. Methods

2.1. Aerodynamic yawing moment and static stability

For judging the effect of an aerodynamic surface (wing, body, and tail) on yaw stability, an appropriate measure is required. Such a measure is available with the concept of static yaw stability given by the derivative of the aerodynamic yawing moment coefficient with respect to the sideslip angle $C_{n\beta}$, as outlined in the following. This concept means that when the bird is disturbed from symmetric flight by a sideslip angle β, the aerodynamic yawing moment N produced must be such as to tend to restore it to the reference condition $\beta = 0$, Fig. 1. Thus, yaw stability requires that the change in the aerodynamic yawing moment with the sideslip angle described by $N = (\partial N/\partial \beta)\beta$ is positive, yielding

$$\frac{\partial N}{\partial \beta} > 0. \tag{1}$$

With the use of the derivative of the non-dimensional yawing moment coefficient, $C_{n\beta}$, which may be termed yaw stability derivative and which is implicitly given by

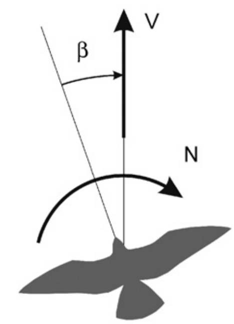

Fig. 1. Sideslip angle and stabilizing yawing moment. The flight condition of the bird shows a positive sideslip angle yielding a yawing moment which tends to restore the symmetric reference $\beta = 0$.

$$N = C_{n\beta}\beta(\rho/2)V^2 Ss \tag{2}$$

(where ρ is the density of the air, V the speed, S the reference area related to the complete wing and s the half wing span), a measure for static yawing stability is available. Using $C_{n\beta}$, the criterion for static yaw stability, Eq. (1), can expressed as

$$C_{n\beta} > 0. \tag{3}$$

The yaw stability derivative $C_{n\beta}$ includes all contributions of the aerodynamic components of the bird having an effect on the yawing moment, i.e. those from the wing, the tail and the body.

The following parts are concerned with the contribution of the tail to the overall yaw stability derivative $C_{n\beta}$ of the bird. For this purpose, several tail forms are considered and evaluated with respect to their aerodynamic moment characteristics and effectiveness concerning the yaw axis.

2.2. Bird tails of rectangle, delta or trapezoid form

There are various forms of the tail in birds, concerning aerodynamic and non-aerodynamic functions (Thomas, 1993 and 1997). For the problem dealt with in this paper, the following forms are considered:

(1) Rectangle form.
(2) Delta form.
(3) Trapezoid form.

Birds with a tail of a rectangular or a similar form are presented in Fig. 2. The tail can be regarded as a small horizontal aerodynamic surface or a slender wing attached to the wing–body combination. For slender shapes as shown in Fig. 2, the tails have extremely small values of the aspect ratio, which is given by

$$A_t = b_t^2/S_t, \tag{4}$$

where b_t is the span and S_t the area of the tail. In case of the rectangular form with $S_t = b_t l_t$, the following relation

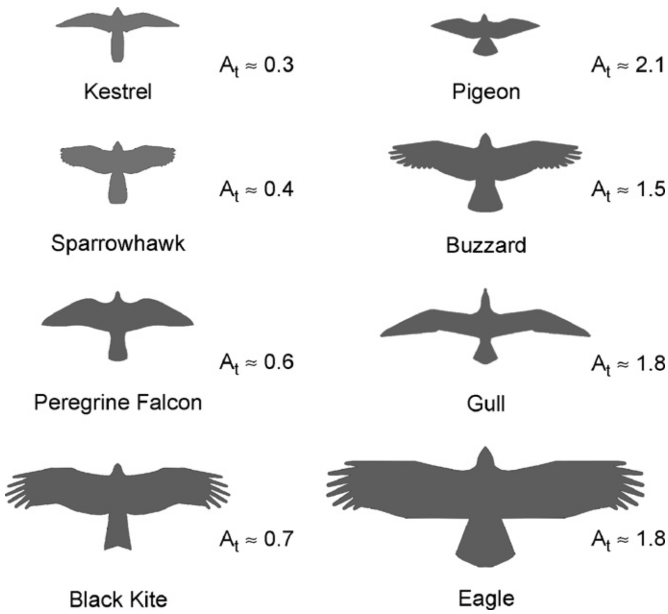

Fig. 2. Bird tails similar to rectangle form (left) and to delta or trapezoid form (right).

holds for the aspect ratio

$$A = b_t/l_t, \tag{5}$$

where l_t is the chord length of the tail which is equal to its overall length here. Data based on an estimation of the tail aspect ratios of a rectangular or similar form are presented in Fig. 2, too.

Tail forms similar to a delta are also shown in Fig. 2. The sweep angle of such tails can be high so that a slender shape results for the delta form. A slender shape corresponds with a very small aspect ratio, which can be expressed for the delta form with $S_t = (1/2)b_t l_t = (1/4)b_t/\cot\varphi_t$ as

$$A_t = 2b_t/l_{t,max} = 4 \cot \varphi_t, \tag{6}$$

where $l_{t,max}$ is the length of the tail and φ_t the sweep angle of the leading edge. From Eq. (6), it follows that the aspect ratio becomes very small for highly swept tails. This manifests also in the aspect ratio data given in Fig. 2.

A tail type, which may be considered a mixed form with regard to the rectangle and delta forms, is the trapezoid, for which examples are presented in Fig. 2. Trapezoid type tails have also a slender shape if they show a corresponding chord-to-span ratio. For a slender shape, the aspect ratios of trapezoid tails are again very small. Estimations on the tail aspect ratios of the trapezoid tail type are also given in Fig. 2.

The tail shape in a bird can vary to a large extent, yielding great changes in its form and size depending on the flight condition (e.g. Thomas, 1993, 1997). The tail may be spread widely in slow flight while it is furled at higher speeds. Thus, the tail in a bird may alternately show a form similar to a rectangle as well as to a delta or trapezoid.

2.3. Aerodynamic methods for determining yawing moment characteristics

The data of the yawing moment characteristics presented in the following sections are based on various aerodynamic methods. These range from approximate procedures to highly sophisticated methods which are capable to deal with the complex flow field of wing–tail combinations due to the mutual aerodynamic interference effects existing between the wing and the tail.

An approximate formula for describing the yawing moment characteristics of aerodynamic surfaces like tails is given in Weissinger (1943). The results compare well with theoretical and experimental data. Data from theory applicable to tail forms are given in Schlichting and Truckenbrodt (2001) and Gronau (1956). Further to the tail forms dealt with in this paper, experimental data were used which are from wind tunnel tests (Bußmann and Kopfermann, 1944; Gronau, 1956; Hummel, 1991, 1992).

From an aerodynamics point of view, a wing–tail combination represents a configuration which is more complex than the wing or the tail alone even if they in themselves show complex geometric features (in terms of plan forms, profiles, etc.). Thus, there is a correspondingly complex structure of the flow field around the wing and the tail because of mutual aerodynamic interference effects between these two elements. For treating such complex configurations, sophisticated aerodynamic methods and efficient computer programs capable of dealing with the interference effects are required in order to obtain a solution for the flow field around the wing and the tail so that the related forces and moments can be determined.

As a representative configuration, the wing–tail combination of a pigeon (Fig. 3) was selected and its yawing moment characteristics have been determined in detail. A modern and efficient aerodynamic method was applied

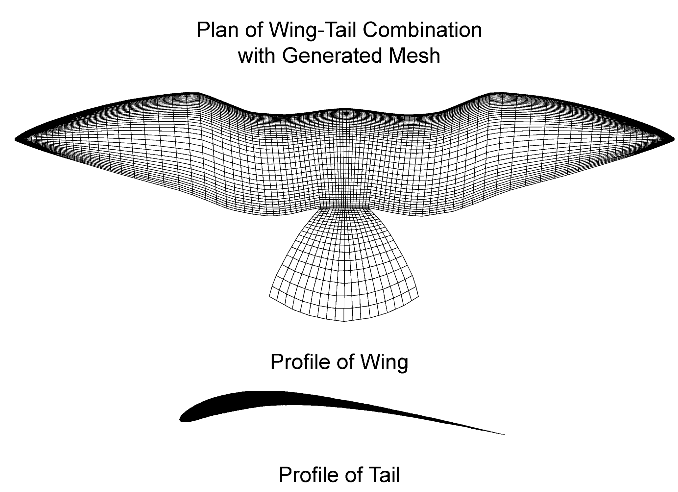

Fig. 3. Modelling of wing–tail combination of pigeon (according to Herzog, 1968). Data: $S = 0.0684\,\mathrm{m}^2$, $s = 0.34\,\mathrm{m}$, $A = 6.8$. Profile of wing: corresponding to pigeon wing given in Herzog (1968). Profile of horizontal tail: NACA2202 (National Advisory Committee for Aeronautics).

to compute the forces and moments with high numerical precision. For this purpose, the FLM-Eu Code was used which is a computer program developed at the Institute of Fluid Mechanics of the Technische Universität München (Cvrlje et al., 2000; Jiang et al., 2003). The FLM-Eu Code is an efficient aerodynamic method for modelling the fluid flow around complex geometries and to compute the forces and moments with high precision. It provides comprehensive modelling capabilities for a wide range of steady and unsteady flows of inviscid, rotational and compressible nature and for complex two-and three-dimensional forms. The calculations are based on a finite-volume approximation to the integral form of the Euler equations.

There are three steps in constructing numerical solutions, yielding a definition of the wing geometry and discretization of the computational domain, an evaluation of flow properties as well as processing of output data.

For determining force and moment characteristics, the geometry of the wing and tail is modelled in regard to their planforms with the generated surface mesh and their profiles, Fig. 3. The surfaces are divided into a large number of grid elements. The profiles of the wing and the tail, also shown in Fig. 3, are assumed to be constant along the spans. For the tail profile, it is assumed that it is thin and shows only a little or no camber. The selected profile has such a characteristic.

3. Results and discussion

3.1. Basic yawing moment characteristics of tails with rectangle, delta or trapezoid form

Tails of a rectangle, a delta or a trapezoid form which are of concern for the yawing moment issue under consideration and shown in Fig. 2 are well suited to generate yawing moments of a significant magnitude in case of a sideslip angle. This particularly holds if tails have a slender shape yielding extremely small aspect ratios. In order to show their significance for the aerodynamic yawing moment characteristics due to sideslip, related aspects of fundamental nature are considered first. For this purpose, the yawing moment characteristics of wings with a very small aspect ratio comparable to the values in bird tails are dealt with. The yaw stability derivative $C_{n\beta}$ introduced in a preceding section is used for describing these characteristics. It is an aerodynamic quantity appropriate for the addressed purpose because it is dependent only on the form of the wing or tail, but not on its size (i.e., not on the area and half wing span) and not on the flight condition (i.e., not on the speed and altitude).

Results are shown in Fig. 4, presenting theoretical and experimental data. From these data, it follows as a basic result that both the rectangle and delta forms show positive values of the yaw stability derivative $C_{n\beta}>0$, thus generating stabilizing yawing moments. Furthermore, $C_{n\beta}$ is of a significant magnitude in the region of small aspect ratios shown in Fig. 4. The effect of the aspect ratio A is

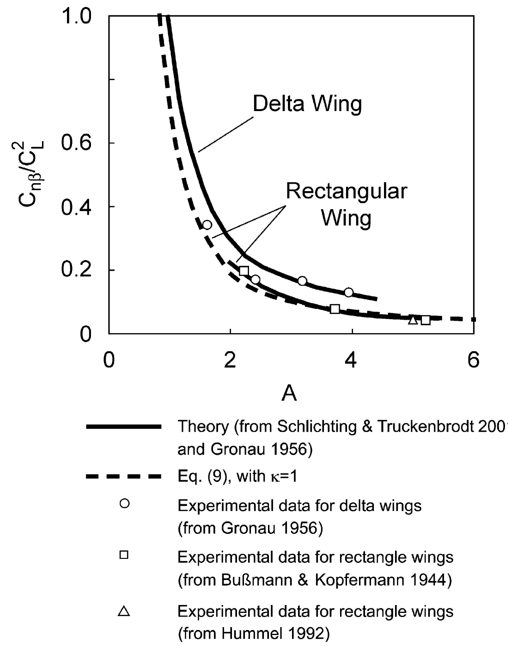

Fig. 4. Yawing moment due to sideslip of wings with low aspect ratio.

strong, yielding a progressive increase of $C_{n\beta}$ with a reduction of A. The increase is particularly pronounced in the region at about $A = 2$ and below where a rise in $C_{n\beta}$ with a steep gradient exists. This region of very small aspect ratios is most important for the yawing moment issue under consideration because it corresponds with the tail values of birds for which data are given in Fig. 2.

Another aspect relates to the fact that the curves for the rectangle and delta forms in Fig. 4 are relatively close to each other. This means that both forms are of similar effectiveness in generating yawing moments. Furthermore, tails, which are not strictly of rectangle or delta type, but employ some mixed form, can be assumed to have a comparable effectiveness. The trapezoid type may be considered as such a mixed form. In this sense, it can be assumed that the data also cover trapezoid type tails in terms of fundamental aerodynamic characteristics.

From the data presented in Fig. 4 it further follows that $C_{n\beta}$ depends also on the lift coefficient C_L, which is given by

$$C_L = \frac{L}{(\rho/2)V^2 S}, \tag{7}$$

where L is the aerodynamic lift. According to Fig. 4, there is basically a quadratic relationship between $C_{n\beta}$ and C_L, yielding

$$C_{n\beta} \propto C_L^2. \tag{8}$$

This relationship is also of relevance for the role of the tail with respect to yaw stability. First, the quadratic dependence means that $C_{n\beta}$ progressively increases with C_L so that it becomes particularly significant in the region of higher lift loadings. Second, $C_{n\beta}$ is independent of the sign of C_L so that it is always positive. As a result, $C_{n\beta}$ is stabilizing, regardless of C_L being positive or negative. This is important with respect to the tail because it may show positive or negative lift loadings (i.e. $C_L > 0$ or $C_L < 0$), depending on the flight condition and the required tail lift for the pitching moment balance.

In Fig. 4, results are also presented using an approximate formula (Weissinger. 1943) for rectangular forms (extrapolated for $A < 4$)

$$C_{n\beta} = \left(\frac{\kappa}{A} + 0.168\frac{A}{A+2} - 0.1\right)\alpha C_L, \tag{9}$$

where α is the angle of attack and κ an empirical factor (ranging from 1.0 to 1.2). From Fig. 4, it follows that these results compare well with the exact values from theory and experiment. This formula makes explicitly evident the substantial effects of A and C_L on $C_{n\beta}$.

From the results derived up to now, it follows that the tails in birds—because of their extremely low aspect ratios—are much more effective in producing yawing moments due to sideslip than bird wings which have significantly larger aspect ratios. Considering an aspect ratio range of about 6–20 as representative for bird wings, the data given in Fig. 4 suggest that the $C_{n\beta}$ values of wings are much smaller than those of tails. Thus, the tail has a potential for a substantial effect on the overall $C_{n\beta}$ of the bird though it is smaller in size.

This consideration is supported by the fact that the size of the tail of a bird can be quite significant when compared with the wing. For example, the ratio of the areas of the tail and the wing in the pigeon depicted in Fig. 3 amounts to about 25%. There may be other birds showing an even higher ratio. Since the effectiveness of the tail as an aerodynamic force and moment producer increases with its size, its relevance for yaw stability is correspondingly enlarged.

3.2. *Yawing moment characteristics of a representative wing–tail combination*

The preceding considerations on the yawing moment characteristics of wings with very small aspect ratio are of fundamental nature, and in this sense they also hold for bird tails of corresponding forms. For showing more concretely the yawing moment characteristics of bird tails, a representative configuration consisting of a wing–tail combination is considered and the mutual flow interactions between these two elements are accounted for. For this purpose, the wing–tail combination of a pigeon (Fig. 3) was selected, and its yawing moment characteristics have been determined in detail.

An evaluation of the force and moment characteristics determined with the described aerodynamic method (FLM-Eu Code, Cvrlje et al., 2000; Jiang et al., 2003) yields the yawing moment coefficient derivative with respect to the sideslip angle $C_{n\beta}$. This is illustrated in Fig. 5, which shows the relationship between $C_{n\beta}$ and the lift coefficient C_L for the wing–tail combination as well as the contribution of the tail. The lift coefficient was varied by changing the angle of attack, with a fixed relation between the wing and the tail. The reference for the yawing moment is the point at the root quarter chord of the wing.

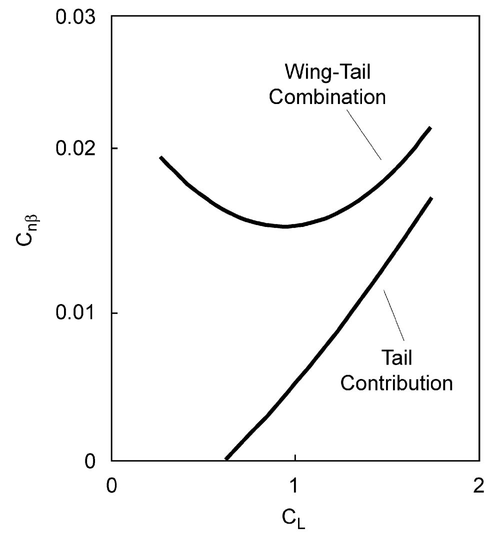

Fig. 5. Yawing moment due to sideslip for wing–tail combination of pigeon (shown in Fig. 3).

Fig. 5 shows that there is yaw stability of the wing–tail combination, manifesting in positive $C_{n\beta}$ values. Furthermore, it follows from Fig. 3 as a main result that the contribution of the tail to $C_{n\beta}$ is substantial. This particularly holds for the region of higher lift coefficients $C_L > 0.8$. Here, the tail effect on yaw stability is even dominant, providing the major contribution. As a result, the tail is essential for the yaw stability in this case.

The relevance of the tail for yaw stability is emphasized by the fact that it is very effective in the higher C_L range at about $C_L = 0.8$ and above which is of importance for gliding flight. It concerns conditions at minimum glide angle or minimum sink rate, corresponding to flights at the maximum of the lift-to-drag ratio C_L/C_D or at the maximum of the ratio $C_L^{3/2}/C_D$, respectively (Brüning et al., 2006). For such flight conditions, lift coefficients at about $C_L = 0.8$ and above are reported (Norberg, 1990). In circling flight, the lift coefficients are also high. There are observations showing circling lift coefficients with mean values of 1.33–1.45 (Pennycuick, 1983). For a pigeon, lift coefficients referenced to the sum of wing and tail areas have values up to 1.3 in gliding flight (Pennycuick, 1968).

The tail lift, which is significant for the contribution of the tail to the yawing moment, is shown in Fig. 6. The tail lift is presented in terms of the lift coefficient $C_{L,t}$ which, referenced to the tail area S_t, is given by

$$C_{L,t} = \frac{L_t}{(\rho/2)V^2 S_t}, \tag{10}$$

where L_t is the lift at the tail. The data depicted in Fig. 6 show that the tail lift coefficient $C_{L,t}$, which increases with the overall lift coefficient, is at a moderate level.

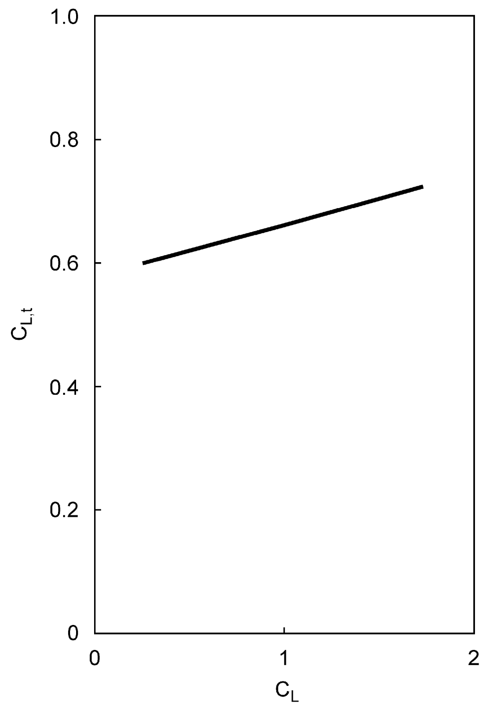

Fig. 6. Tail lift of wing–tail combination of pigeon (shown in Fig. 3), $C_{L,t}$ referenced to tail area S_t.

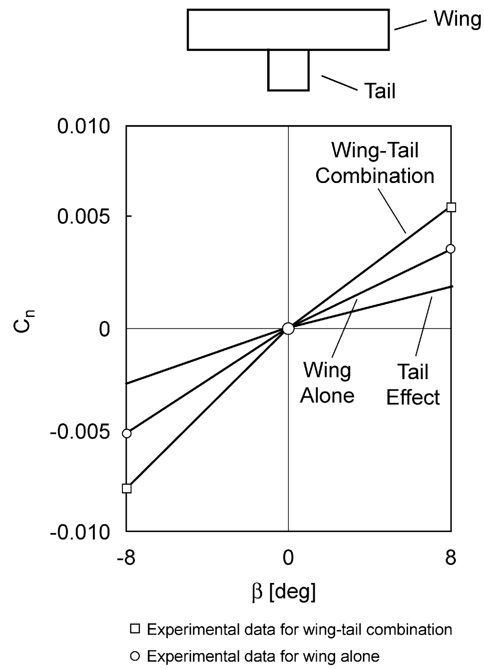

Fig. 7. Yawing moment of a wing–tail combination due to sideslip from wind tunnel measurements (experimental data from Hummel, 1992). Data: $S_t/S = 0.2$, $A = 5$, $A_t = 1$, $\alpha = 9.5\,\deg$.

3.3. Evaluation and discussion of experimental data

There are experimental data from wind tunnel tests on wing–tail combinations which are concerned with the aerodynamic moment characteristics in the pitch, roll and yaw axes (Hummel, 1991, 1992). With an evaluation of these data, it is possible to derive results on the effects of the tail on yaw stability.

The investigated wing–tail combination is shown in Fig. 7, depicting a rectangular wing to which a rectangular tail is attached. Data for the areas and the aspect ratios of the wing and the tail, relevant for the influence of the tail on the yawing moment characteristics, are given in Fig. 7, too.

The yawing moment coefficient of the wing–tail combination

$$C_n = \frac{N}{(\rho/2)V^2 Ss} \tag{11}$$

is also shown in Fig. 7. Basically, there is a significant effect of β on C_n for the wing–tail combination, yielding a considerable increase of C_n with β and providing stability in yaw ($C_{n\beta}>0$). Furthermore, data for the wing alone are also shown. The difference between the values of the wing–tail combination and the wing alone represents the effect of the tail on the yawing moment. As a main result, it follows from the data presented in Fig. 7 that the tail provides a considerable contribution to the yawing moment. This contribution amounts to more than 30% of the total yawing moment of the wing–tail combination.

There are two aspects, which further elucidate the effectiveness of the tail for generating yawing moments. The first concerns the yawing moment and the size of the tail in comparison with the wing. The tail area is only 20% of that of the wing. But the contribution of the tail to the yawing moment is about 50% when compared with the contribution of the wing. This shows how effective the tail with its extremely low aspect ratio is in generating yawing moments. The second aspect relates to the fact that the lift loading of the tail concerning the data presented in Fig. 7 is rather small, yielding a lift coefficient of about $C_{Lt} = 0.3$ (with C_{Lt} referenced to the tail area S_t). Though this is a small value of C_{Lt}, the tail contribution to $C_{n\beta}$ is considerable. For higher tail lift coefficients, it can be assumed that the tail contribution becomes larger. This is due to the fact that the effect of the lift coefficient on the static yaw stability metric progressively increases, as shown in the general treatment of basic yawing moment characteristics of rectangular wings in a preceding section (Fig. 4).

3.4. Physical mechanisms of tail effects on yaw stability

There are specific effects which support the tail in its stabilizing role and which are not relevant for wings. Basically, there are two effects of the tail on the yawing moment, one holding generally for tails and wings while the other one is specific for the tail. These effects are considered in the following treatment which is also intended to provide an insight into the physical mechanisms generating the yawing moment of the tail due to sideslip.

The first effect is due to an asymmetry in the airflow at the tail or the wing in case of a sideslip angle. This asymmetry leads to an asymmetrical lift distribution caused by the sideslip angle, yielding an increase at the advancing tail half and a decrease at the other. The asymmetrical lift distribution causes a correspondingly asymmetrical induced-drag distribution such that there is a drag increase at the advancing tail half, denoted by $\Delta D_{t,r}$, and a drag decrease at the other, denoted by $\Delta D_{t,l}$, as schematically shown in Fig. 8. These drag changes which are opposite in sign form a couple if it can be assumed that they are of equal size, i.e.

$$\left|\Delta D_{t,r}\right| = \left|\Delta D_{t,l}\right|. \tag{12}$$

The couple yields a yawing moment given by

$$N_{t1} = \Delta D_{t,l} y_{lr}, \tag{13}$$

where y_{lr} is the distance between $\Delta D_{t,r}$ and $\Delta D_{t,l}$. Since N_{t1} acts against the sideslip disturbance, it has a stabilizing influence. This is valid for positive as well as for negative lift at the tail because the relationship between the drag changes $\Delta D_{t,r}$ and $\Delta D_{t,l}$ remains basically unchanged, i.e. $\Delta D_{t,r}$ is directed forwards and $\Delta D_{t,l}$ rearwards independent of the sign of the tail lift as shown in Fig. 8.

It is noteworthy that the overall drag of the tail D_t is not changed by $\Delta D_{t,r}$ and $\Delta D_{t,l}$, Fig. 8. This holds if $\Delta D_{t,r}$ and $\Delta D_{t,l}$ form a couple, meaning that they are equal in size but different in sign. Thus, the sum of $\Delta D_{t,r}$ and $\Delta D_{t,l}$ is zero. As a result, the overall drag, given by D_t, is not changed.

The overall drag of the tail D_t yields also a yawing moment because the point at which it acts is behind the center of gravity (Fig. 8). This moment is given by

$$N_{t2} = D_t r_t \sin \beta. \tag{14}$$

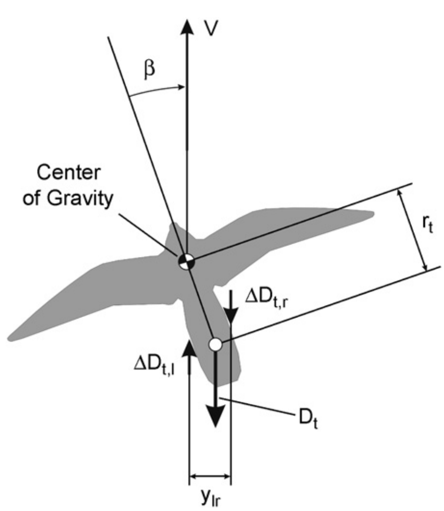

Fig. 8. Effect of ΔD_{tl}, ΔD_{tf} and D_t on the yawing moment: (a) The asymmetrical induced-drag changes ΔD_{LI} and ΔD_{1r} which are caused by the sideslip angle β form a couple if they are of the same magnitude. This couple yields a stabilizing yawing moment given by $N_{lr} = \Delta D_{t,l}\, y_{lr}$. (b) The force D_t represents the overall tail drag which is not changed by ΔD_{tr} and ΔD. It produces also a stabilizing yawing moment given by $N_{t2} = D_t r_t \sin\beta$.

There are several points, which are of interest with regard to N_{t2}. From Eq. (14), it follows that the contribution of D_t to the yawing moment increases with r_t. Thus, it becomes more important for birds with long tails. Furthermore, N_{t2} is always existent independent as to whether the tail generates lift or not. This is because D_t is made up of the zero-lift drag and the lift dependent drag. While the lift-dependent drag vanishes for the case of an unloaded tail showing no lift, the zero-lift drag is still there. Thus, there is a yawing moment N_{t2} in the case of zero tail lift. Here again, the stabilizing effect of the yawing moment N_{t2} holds for positive as well as for negative lift at the tail.

The yawing moment N_{t2} at the tail represents a difference to the yawing moment of wings. This is because the drag of the wing has no or only a negligible lever arm with respect to the yaw axis.

3.5. *Other tail configurations and related effects on yaw stability*

In the preceding section on the physical mechanisms of tail effects on yaw stability, a treatment of basic nature about the effect of the drag at the tail on yaw stability is given. In this basic sense, the treatment also holds for other tail forms which differ from that dealt with in the preceding section. There is a great variety of tail shapes in birds, showing most elaborate forms and having different functions (Thomas, 1993, 1997). Beyond the tail forms considered up to now, there are ornamental tails such as deep forks or pintails. In the following, considerations are presented on such tail configurations concerning possible effects on yaw stability.

With regard to yaw stability, ornamental tails are of interest, which have a great elongation in relative terms (i.e., compared with the body or the wing). There are tail lengths up to eight times that of the body (Thomas, 1997). Tails with a great elongation can show a high drag level (Norberg, 1996). The tail drag can be larger than the drag of the wing and the body. It can be assumed that long tails are particularly suited to contribute to yaw stability. The physical mechanism is similar to the one considered in the preceding section.

Another configuration concerns forked tails which show drag forces at the elongated tail elements on the left and right sides. These drag forces have different lever arms with respect to the center of gravity in case of a sideslip angle and possibly dissimilar magnitudes. Thus, they generate different yawing moments. It can be assumed that the difference in the yawing moments due to the forces on the right and left sides yields a resultant moment, which is stabilizing.

A further ability for producing stabilizing yawing moments is due to the legs and feet, possibly in combination with the tail. In Fig. 9, two aerodynamic configurations of birds are presented which show extended feet.

One is a crane the feet of which is carried near the body and extends over the tail. Depending on their length, they

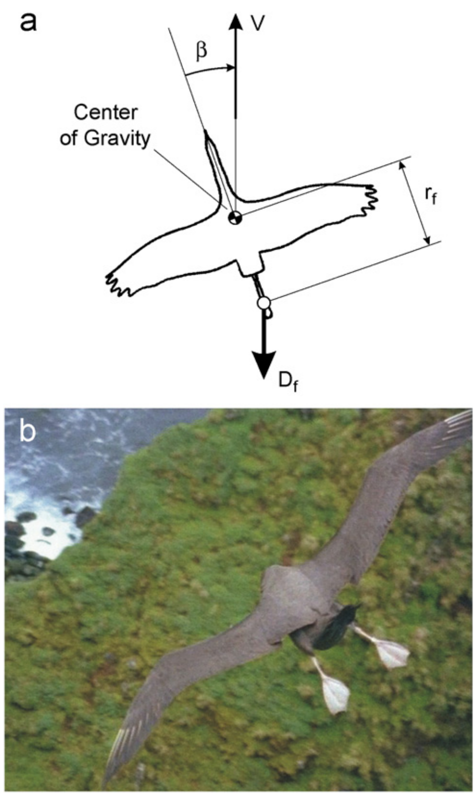

Fig. 9. Yawing moment due to extended legs/feet: (a) Upper part—crane, normal-speed flight. (b) Lower part—abatross, low-speed flight, photo from Parer and Parer-Cook (1994).

can stretch out in rearward direction to a considerably larger extent than the tail. For the crane, Fig. 9 schematically shows how the drag at the legs and feet generates a yawing moment in case of a sideslip disturbance. This yawing moment is given by

$$N_{t3} = D_f r_f \sin \beta. \tag{15}$$

As a result, the yawing moment caused by the drag of the legs and feet is directed against the sideslip disturbance, thus yielding a positive contribution to yaw stability. The extended feet configuration of the crane relates to normal flight speeds.

Another configuration involving legs and feet is also shown in Fig. 9. In normal flight, the feet are carried in a streamlined position producing little or no drag. In the low speed flight condition shown in Fig. 9, the feet are lowered so that they are exposed to the airflow and generate drag. This is an issue of flight performance as well as yaw stability. Concerning the effectiveness of the lowered feet as a drag generator, webbed feet are particularly suited since they possess a comparatively large wetted area in the airflow (Fig. 9). This contributes to both goals of performance enhancement and yaw stability improvement, which is considered in the following paragraph. With regard to flight performance, the lowered feet reduce the lift-to-drag ratio of the bird due to the drag increase (Pennycuick, 1975). Thus, the lowered feet can be used to steepen the angle of glide, yielding an advantage when approaching a landing place, or to soar in a strong upwind and holding the altitude constant.

The influence of lowered feet on yaw stability in low speed flight is also due to their drag. The physical mechanism underlying the effect of the feet drag on the aerodynamic yawing moment is basically similar to the case of the crane. Since the configuration shown in Fig. 9 yields a separation distance between the feet, the drag effect of each foot needs to be accounted for. In terms of a resultant yawing moment of both drag forces, there is a stabilizing effect.

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