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Why Birds and Miniscale Airplanes Need No Vertical Tail

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The vertical tail is a typical component of the aerodynamic configuration of airplanes, existing with any kind of vehicle. In contrast, there is no bird which possesses a vertical tail. This is a striking difference between birds and airplanes with regard to the ability of flight. The functions of the vertical tail are considered in this paper, including issues of flight dynamics as well as control and trim. It is shown that there are unique relationships for the flight mechanics of small flying objects, like birds and miniscale airplanes, and for their aerodynamic configuration so that they need no vertical tail. It turns out that small flying objects can have an adequate level of dynamic yaw response capability (Dutch roll frequency) even if their static aerodynamic stability is very small. Furthermore, it is shown that the wing alone can provide the required aerodynamic yawing moment if it has appropriate features. For identifying these features, results from flow simulation using a sophisticated aerodynamic method are presented. For this purpose, a modern and efficient aerodynamic method was used for modeling the fluid flow around complex geometries and for computing the forces and moments with high precision. Other dynamics issues dealt with concern the damping characteristics in the yaw axis. It is shown that there is a reduction in the required aerodynamic damping capability with a decrease in the size. As a result, the wing alone can generate the required level of yaw damping. Furthermore, the effects on the spiral mode are treated. It is shown that the abandoning of the vertical tail is only of partial influence. The control and trim issues dealt with concern asymmetrical flight for which a yawing moment capability is usually required. It is shown how it is possible to cope with such flight conditions without needing a vertical tail. Aerodynamic configurations needing no vertical tail are an issue which is of relevance for technical applications. From the characteristics of birds, it can be learned how such configurations and the related benefits may be used for airplanes. This is of particular significance for miniscale airplanes the size of which is considered to range from configurations comparable with large birds to micro air vehicles with a length of some centimeters.

Nomenclature

A = aspect ratio
C_L = lift coefficient
C_l = rolling moment coefficient, $C_l = 2L/(\rho V^2 Ss)$
$C_{li} = \partial C_l/\partial i$ = $i = rs/V,\ ps/V,\ \beta,\ \delta_a$
C_n = yawing moment coefficient, $C_n = 2N/(\rho V^2 Ss)$
$C_{ni} = \partial C_n/\partial i$ = $i = rs/V,\ \beta,\ \delta_a,\ \delta_r$
g = acceleration due to gravity
i_z = radius of gyration
m = mass
rS = yaw rate
S = reference area
s = half span
s_s = eigen value of spiral mode
V = speed
α = angle of attack
β = sideslip angle
γ = flight path angle
δ_a = roll control
δ_r = yaw control
ζ_d = Dutch roll damping ratio
μ = relative mass parameter, $\mu = 2m/(\rho Ss)$
ρ = air density
φ = sweep angle
ω_{nd} = undamped natural frequency of Dutch roll

Introduction

THE vertical tail is a typical component of the aerodynamic configuration of airplanes. It is attached at the rear of the fuselage, forming a small wing in the vertical plane. The vertical tail can be found with any type of airplanes, ranging from motorless gliders and small aircraft to the largest transports or the fastest supersonic vehicles and even aerospace craft. In contrast, there is no bird which possesses a vertical tail. This is a striking difference between birds and airplanes with regard to the ability of flight. Lacking of the vertical tail in birds contrasts with the fact that they have in common with airplanes the other aerodynamic components which are essential for the ability of flight, i.e., the wing, the body, and the horizontal tail.

There are various functions of the vertical tail. One is yaw stability for which the vertical tail is of predominant importance. The stability in bird flight is the subject of recent papers [1–3], yielding important results in this field. Focus is placed on the longitudinal motion. As far as yaw stability is concerned, considerations are given in qualitative terms. Furthermore, research on the stability of soaring birds was performed using radio controlled models [4,5]. It provides valuable results on the stability properties of the lateral-directional motion. A central issue which is the subject of recent research [6,7] concerns the question of how yaw stability in birds is achieved and why they do not need a vertical tail for this purpose. In particular, what feature in the aerodynamic configuration of birds can take over the function which the vertical tail has for yaw stability.

There are other functions for which the vertical tail is also of primary importance. These concern the damping of yaw motions as well as the control and trim of asymmetrical flight conditions (e.g., [8,9]). Here again, the question is what features in an aerodynamic configuration without a vertical tail can take over these functions.

With respect to the research on bird flight, it is only partially known why birds need no vertical tail. It is therefore the purpose of this paper to provide a contribution for clarifying this problem. It will be shown that there are unique relationships for the flight mechanics of small flying objects, like birds and miniscale airplanes, and for their aerodynamic configuration so that they need no vertical tail.

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These relationships concern all functions of the vertical tail. It will be shown how these functions are accomplished in birds without requiring a vertical tail.

Another issue of this paper is the use of aerodynamic configurations needing no vertical tail in technical applications. From the characteristics of birds, it can be learned how such configurations and the related benefits may be used for airplanes. This is of particular relevance for miniscale airplanes which may be comparable in size with birds. Accordingly, the size of such airplanes is considered to range from configurations showing wing spans of about 3–4 m to micro air vehicles the dimension of which is less than 15 cm in length, width, or height (e.g., [10]).

Aerodynamic Functions of the Vertical Tail

The vertical tail has aerodynamic functions and purposes which are due flight mechanics requirements. According to these functions, it has to provide the following capabilities (e.g., [8,9]): 1) stability in the yaw axis, 2) damping of yawing oscillations, and 3) control and trim of asymmetrical flight conditions.

The stability capability (No. 1) is twofold: The first point concerns static stability in the yaw axis, given by the aerodynamic moment derivative $C_{n\beta} = \partial C_n/\partial\beta$. The vertical tail exerts a stabilizing effect, yielding

$$C_{n\beta} > 0 \tag{1}$$

The second point of the stability capability of the vertical tail concerns the dynamics characteristics in the yaw axis. This basically means that the dynamic action generated by the aerodynamic moment of the vertical tail for acting against a sideslip disturbance to restore the symmetric flight condition ($\beta = 0$) has to be fast enough. It can be described by the frequency of the Dutch roll, with the objective to exceed a required minimum value. A more detailed treatment of this issue will be given in a subsequent section.

With regard to the damping capability of the vertical tail (No. 2 from previous paragraph), the yaw rate leads to a change in the local flow direction at the vertical tail so that there is an aerodynamic yawing moment, given by the damping derivative $C_{nr} = \partial C_n/\partial(rs/V)$, which acts in a direction opposite to the yaw rate. Thus, the vertical tail exerts a damping effect, yielding

$$C_{nr} < 0 \tag{2}$$

The significance of this damping effect for motions in the yaw axis, particularly for the Dutch roll, and the magnitude which may be required will be considered in a subsequent section.

The capability for control and trim of asymmetrical flight conditions (No. 3 from previous paragraph) concerns the rudder as the movable part of the vertical tail. A rudder deflection causes an aerodynamic yawing moment, given by the rudder derivative $C_{n\delta r} = \partial C_n/\partial\delta_r$, to yield

$$C_{n\delta r} < 0 \tag{3}$$

For the preceding capabilities numbers 1–3 and the related aerodynamic functions, the vertical tail provides the main, or even the only, contribution. In airplanes, the contribution of the vertical tail to the total C_{nr} usually amounts to about 80 or 90% (e.g., [11]). The vertical tail is essential for $C_{n\beta}$ to overcome the destabilizing fuselage effect. Its contribution to $C_{n\delta r}$ is 100%. The question arises how these aerodynamic functions can be accomplished without a vertical tail in flying objects, like a bird or a miniscale airplane. This concerns the following topics which will be addressed in the subsequent sections: 1) yaw dynamics and related requirements on aerodynamic moments, with focus on yaw stability (static and dynamic) and yaw damping; 2) wing features enhancing the ability for generating aerodynamic yawing moments; and 3) control/trim requirements for the yaw axis in asymmetrical flight.

Yaw Dynamics Aspects

Yaw dynamics are a part of the entire lateral-directional dynamics of flying objects, like birds or airplanes. The lateral-directional dynamics show the following modes of motion: 1) Dutch roll, 2) roll mode, and 3) spiral mode.

With regard to the aerodynamic moment characteristics for which the vertical tail is of predominant importance ($C_{n\beta}, C_{nr}$), the Dutch roll is of primary concern. This is because it is substantially influenced by $C_{n\beta}$ and C_{nr}. There is also an influence on the spiral mode, whereas there is usually a small or negligible relationship with the roll mode. Therefore, focus of the following treatment is on the Dutch roll and the spiral mode. They are characterized by frequency and damping properties which can be approximately expressed for the Dutch roll as

$$\omega_{\mathrm{nd}} \approx \frac{s}{i_z}\sqrt{\frac{g}{s}\frac{C_{n\beta}}{C_L}} \qquad \zeta_d \approx -\frac{1}{2}\frac{g}{V}\left(\frac{s}{i_z}\right)^2\frac{C_{nr}}{C_L\omega_{\mathrm{nd}}} \tag{4}$$

and for the spiral mode as

$$s_s \approx -\frac{g}{V}\left(\frac{C_{lr}}{C_{lp}} - \frac{C_{l\beta}}{C_{lp}}\frac{C_{nr}}{C_{n\beta}}\right) \tag{5}$$

These expressions show how the vertical tail exerts an effect on yaw dynamics via the aerodynamic moment derivatives $C_{n\beta}$ and C_{nr}. The stability derivative $C_{n\beta}$ has a primary influence on the frequency of the Dutch roll. The derivative C_{nr} has a likewise significant effect on the damping of this mode of motion. As a result, the vertical tail is of predominant importance for the Dutch roll in a similar manner as it is for the aerodynamic moment derivatives $C_{n\beta}$ and C_{nr}. With regard to the spiral mode, the effect of the tail manifests in the ratio $C_{nr}/C_{n\beta}$ which is of partial influence on this mode.

Dutch Roll Stability and Related Requirements on Aerodynamic Yawing Moment Characteristics

The frequency given in Eq. (4) concerns both points of the previous stability function of the vertical tail (No. 1), i.e., static stability and the dynamic action in terms of a fast restoring capability.

For static stability, it is required that $C_{n\beta} > 0$. This holds if the Dutch roll is existing as an oscillatory mode showing a frequency $\omega_{\mathrm{nd}} > 0$, Eq. (4). Therefore, the frequency properties considered in the following include the static stability issue.

A fast restoring capability in the yaw axis can be ensured by setting up a requirement for an adequate level of the Dutch roll frequency. Accordingly, ω_{nd} has to reach a minimum value, yielding

$$\omega_{\mathrm{nd}} \geq \omega_{\mathrm{nd,min}} \tag{6}$$

Applying this minimum value, a relation can be derived for the required yaw stability derivative in the yaw axis such that

$$C_{n\beta} \geq C_{n\beta,\mathrm{min}} \tag{7}$$

Using Eq. (4), an expression is obtained for $C_{n\beta,\mathrm{min}}$ to yield

$$C_{n\beta,\mathrm{min}} = \frac{s}{g}\left(\frac{i_z}{s}\right)^2 C_L\omega^2_{\mathrm{nd,min}} \tag{8}$$

When considering scaling relations with respect to the effect of size in flying objects (like birds), it can be assumed for the relationship between the radius of gyration and the half wing span that $i_z \sim s$ [6]. Thus, i_z/s is approximately constant, showing an independency of the size. It follows then from Eq. (8) that the required minimum of the yaw stability derivative $C_{n\beta,\mathrm{min}}$ depends on the absolute size manifesting in the half wing span, yielding

$$C_{n\beta,\mathrm{min}} \sim s$$

This relation shows that the required value of $C_{n\beta,\mathrm{min}}$ is decreased in small flying objects when compared with larger ones. As a

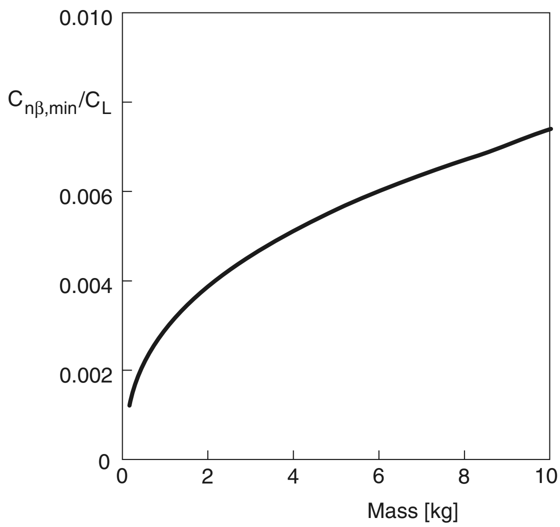

Fig. 1 Required yaw stability $C_{n\beta,\min}$ for birds.

consequence, a vertical tail may not be needed if a flying object is so small that the wing alone can generate the required yawing moment.

For determining the required value of $C_{n\beta,\min}$ to achieve a sufficiently fast restoring capability in terms of $\omega_{\mathrm{nd,min}}$, data may be used which are available from the experience with airplanes concerning response and restoring characteristics in the yaw axis. For this purpose, reference is made to existing flying qualities requirements for specifying $\omega_{\mathrm{nd,min}}$ [12,13]. There are minimum values of 0.4 rad/s (related to gradual maneuvers without precision tracking, and accurate flight path control may be required) and 1.0 rad/s (related to rapid maneuvering, precision tracking, or precise flight path control). A value of $\omega_{\mathrm{nd,min}} = 1.0$ rad/s is selected in this paper as a conservative reference. Furthermore, a value of $i_z/s = 0.22$ is used which is regarded also as a conservative estimate for the radius of gyration of birds in the yaw axis and which can be assumed to hold approximately for birds of any size [6]. For the relationship between the half wing span and mass, the following expression is applied $s = 0.5825m^{0.394}$, with reference made to data given in [14]. Results on the required yawing moment derivative $C_{n\beta,\min}$ from an evaluation of Eq. (8) are presented in Fig. 1. From these results it basically follows that the required $C_{n\beta,\min}$ values are very small for birds. Furthermore, Fig. 1 shows that the required $C_{n\beta,\min}$ values are progressively reduced with a decrease in the size of birds.

The most important result from Fig. 1 is that the required $C_{n\beta,\min}$ values can be achieved with the wing alone, without needing a vertical tail. This will be shown in the following section. Particular emphasis is placed on those features in bird wings which efficiently augment the ability to generate stabilizing yawing moments.

Aerodynamic Moment Characteristics of Bird Wings Related to Yaw Stability

Representative Wing Forms of Birds

From a yaw stability point of view, wing forms in many birds may be grouped into the following two categories (Fig. 2):

1) Bird wings that have sweep. Typically, the sweep is at the outer part of the wing. The wings employ pointed tips.

2) Bird wings that have slotted tips. The slotted tips which are formed by separated feathers are attached to a base wing. The base wing has little or no sweep.

Both features (sweep and slotted tips) are most important for the ability of the wing to generate stabilizing yawing moments. This will be shown in the following by considering two wings which can be regarded as representative for each category. The wings are presented in Fig. 3, depicting a wing with sweep and a wing with slotted tips. The wing with sweep relates to the gull (Fig. 2), with data used for the planform and profile from [15]. The wing with slotted

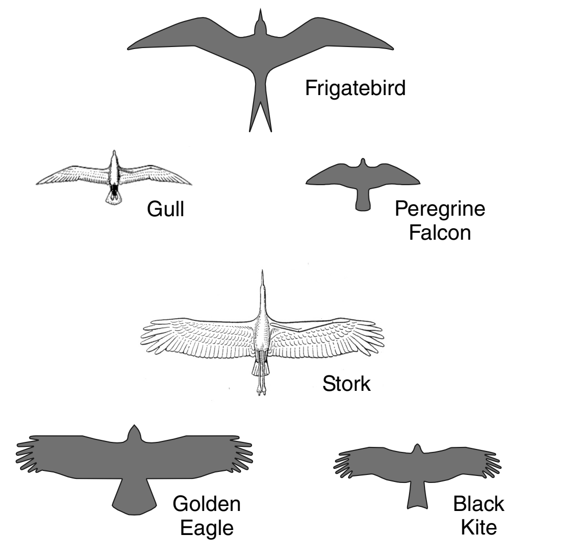

Fig. 2 Wing forms of birds with sweep at outer part or with slotted tips (gull and stork from [15]).

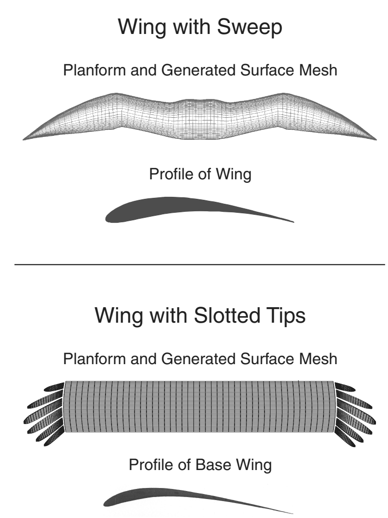

Fig. 3 Wing forms of birds with sweep or with slotted tips.

tips (Fig. 3) is a configuration of generic nature, considered as representative of bird wings with sweep in their slotted tips. It is related to a stork wing (Fig. 2) to use a realistic reference. It shows typical characteristics of bird wings with slotted tips. This particularly concerns sweep, size, and arrangement of the feathers at the tips as well as their relation to the base wing which is modeled as an unswept part. Furthermore, profiles and thickness ratios of the base wing and the feathers have been selected to represent realistic relationships. With regard to the base wing, reference is made to a stork [15]. For the wing tip feathers, a NACA 2202 profile was selected.

Computational Aerodynamics Method for Complex Wing Forms

From an aerodynamics point of view, the two wing forms have a rather complex geometric form. Thus, there is a correspondingly complex structure of the flowfield. This particularly holds for the wing with slotted tips because of mutual interference effects between all elements (base wing and slotted tips). For dealing with such complex forms, sophisticated aerodynamic methods and efficient computer programs are required to obtain a solution for the flowfield around the wing and the slotted tips so that the related forces and moments can be determined.

For determining the yawing moment characteristics of the two wing forms, the FLM-Eu Code [16,17] was used, which is a computer program developed at the Institute of Fluid Mechanics of

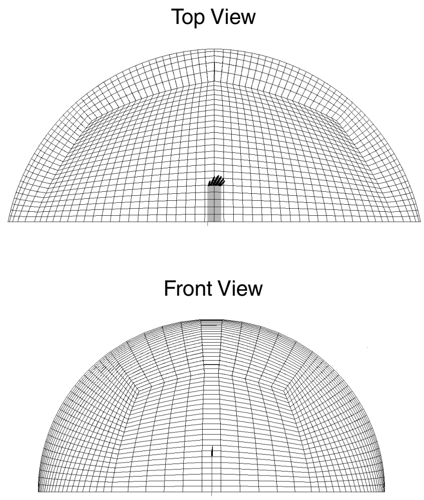

Fig. 4 Computational domain for simulation of flowfield around the wing with slotted tips.

the Munich University of Technology. It is a modern and efficient aerodynamic method for modeling the fluid flow around complex geometries and for computing the forces and moments with high precision. It provides comprehensive modeling 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. Details are given in the following for the wing with slotted tips as the more complex problem (when compared with the gull wing).

With regard to the geometry of the wing, reference is made to Fig. 3. This figure shows the planform of the base wing and the slotted tips as well as the generated surface mesh. The distribution of the angle of attack in the spanwise direction is regarded as constant for the base wing as well as for the planar separated feathers.

The computational domain concerns the space which is considered as relevant for the flowfield associated with the wing and the slotted tips and for which the flow properties are determined. A discretization of the computational domain is performed by specifying the boundaries, the wing geometry, and the mesh topology, as well as by generating a corresponding mesh. An illustration is given in Fig. 4 which shows the computational domain for the wing with the slotted tips on the right. The object in the center is the base wing half with the corresponding slotted tips.

A block topology model is generated which shows a number of appropriate blocks forming the computational domain. The block topology for the wing and the slotted tips is presented in Fig. 5. The blocks are shown for the near-field of the base wing half on the right with the corresponding slotted tips. The base wing and the slotted tips are indicated using a gray shade. The blocks are given by the adjacent elements formed by lines. The mesh generation in the computational domain as well as on the surfaces of the wing and the slotted tips is performed using a distribution for each block along its edges. It is necessary to concentrate a major number of points in critical regions such as in leading- and trailing-edge sections of the main wing and the slotted tips. The point distribution also becomes denser in the regions close to the surfaces of the wing and the slotted tips. The points on the surfaces and within the blocks are generated by interpolation. With regard to the generated mesh on the surfaces of the wing with slotted tips, a further development is attained by improving the smoothness as well as the orthogonality of the grids. The initial grid is smoothed by solving a system of Poisson vector equations.

The output of the calculations consists of data on the geometry, mesh connectivity, and flow properties including density, velocity components in three directions, pressure, and internal energy. To interpret the output data, it is necessary to do a postprocessing by using an appropriate code.

Results on Aerodynamic Moment Characteristics of Bird Wing Forms

Results on the aerodynamic yawing moment characteristics of the wing with slotted tips are presented in Fig. 6 which shows the yaw stability derivative $C_{n\beta}$ as a function of the lift coefficient. From this figure, it follows as a basic result that the wing yields positive $C_{n\beta}$ values, thus producing a stabilizing yawing moment which acts against a sideslip disturbance. Furthermore, Fig. 6 shows that the lift coefficient exerts a significant influence, yielding a strong increase of $C_{n\beta}$ with C_L. The $C_{n\beta}$ values are especially large in the region above $C_L = 0.8$ which can be considered as particularly relevant for the gliding flight of birds [6].

The fact that there is a large stabilizing yawing moment of the wing with slotted tips is primarily due to their sweep. To make this effect more perspicuous, a wing configuration with a modification of the slotted tips is considered which employs no sweep. This configuration has the same geometric properties (size, form, profiles, etc.) as the original wing, but without sweep in the slotted tips. Results concerning the wing without sweep in the slotted tips are also presented in Fig. 6. There is a significant decrease in $C_{n\beta}$ for the

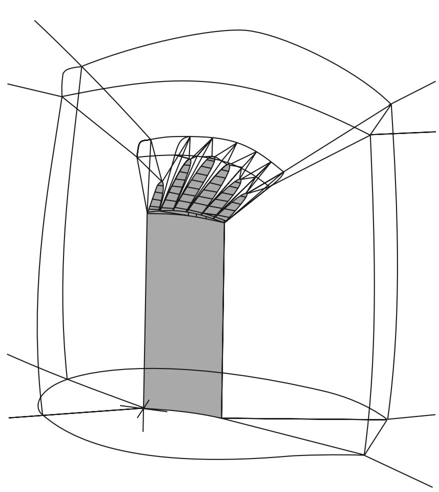

Fig. 5 Block topology of the computational field around the wing with slotted tips (view from below).

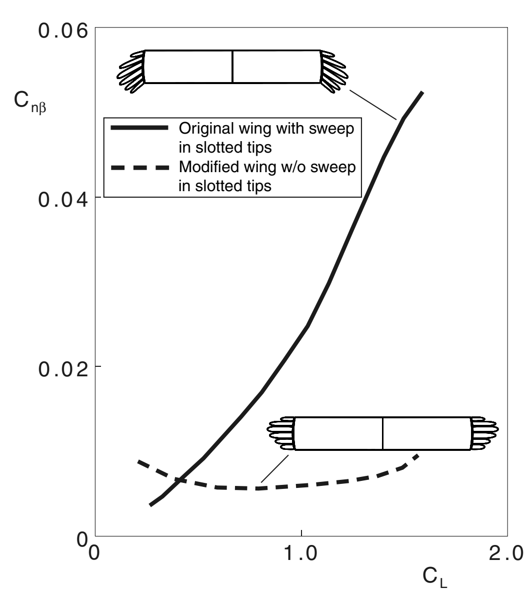

Fig. 6 Yawing moment due to sideslip of wing with slotted tips.

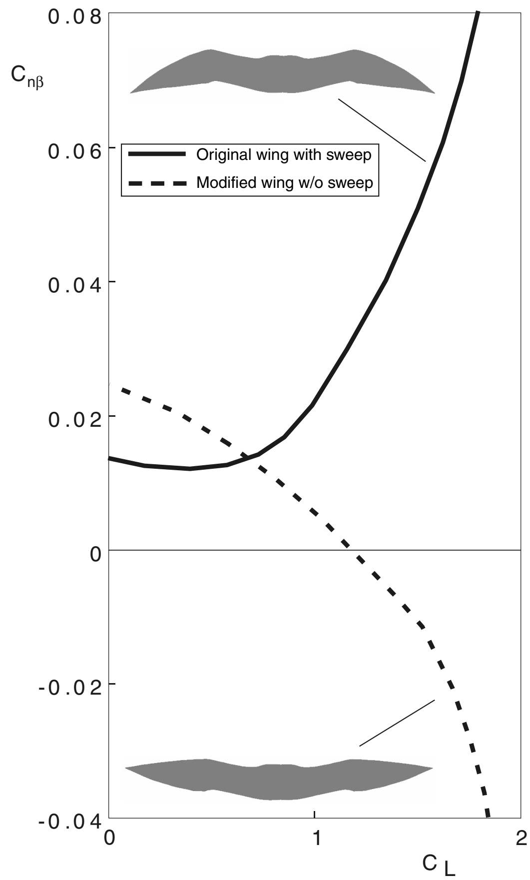

Fig. 7 Yawing moment due to sideslip of wing with sweep.

wing configuration without sweep in the slotted tips when compared with the original wing tip configuration. This especially holds for the higher lift coefficient range which is of particular relevance for gliding flight. The described behavior emphasizes the importance of sweep in the slotted wing tips for yaw stability.

Results on the aerodynamic yawing moment characteristics of the gull wing with sweep at the outer part the aerodynamic features of which are shown in Fig. 3 (planform with generated surface mesh, profile) are presented in Fig. 7. Here again, the wing generates a stabilizing yawing moment $C_{n\beta}$ of significant magnitude. There is a pronounced increase in the stabilizing yawing moment with C_L.

The strong stabilizing effect of the sweep at the outer part can be made perspicuous by considering a wing modification which shows no sweep at its outer part. Results on this modification are also presented in Fig. 7. As a main result, $C_{n\beta}$ of the configuration without sweep in the outer part is substantially decreased when compared with the data of the original wing with sweep. The difference increases with the lift coefficient. It is especially large in the higher lift coefficient range which is of particular interest for gliding flight. The described characteristics emphasize the importance of wing sweep for the yawing moment characteristics.

There is a further point concerning the importance of the sweep in the original wing. It relates to the fact that the modified wing even shows negative $C_{n\beta}$ values (Fig. 7). This means that it would produce instability. The reason for the negative $C_{n\beta}$ values is that the inner part of the wing employs sweep in forward direction, yielding a sign change of $C_{n\beta}$. This result further emphasizes the importance of the sweep for yaw stability, as existing in the original wing.

The data presented in Fig. 7 for the wing employing pointed tips show as a main result that wing sweep (in terms of sweepback) is most efficient for generating favorable yawing moments and, thus, can be rated as of primary significance for achieving yaw stability.

There is a feature which is noteworthy to address because it enhances the efficiency of wing sweep to generate stabilizing yawing moments. This feature concerns the wing region which employs sweep. In both wing forms (the wing with slotted tips as well as the one with pointed tips), the sweep is at the outer part of the wing. This enhances the yawing moment efficiency; the underlying physical mechanism is described in the following. The yawing moment due to sideslip is primarily caused by the asymmetrical induced-drag changes at the left and right wing half (i.e., showing an increase at the right wing half and a decrease at the left one or vice versa). These asymmetrical induced-drag changes are associated with the asymmetrical lift distribution generated by the sideslip angle. The yawing moment is the product of the asymmetrical induced-drag changes and the related lever arms with respect to the yaw axis. For given drag changes, the yawing moment is larger, the larger the lever arms are. At the outer part of the wing, drag changes have a larger lever arm than drag changes have at the inner part. Using sweep at the wing means to increase the induced-drag change due to sideslip. With sweep at the outer wing part, the increase in the induced-drag change is combined with the larger lever arm. As a result, sweep at the outer part of the wing is most efficient for generating yawing moments.

There is another important point with regard to the ability of wings to generate stabilizing yawing moments. This concerns small birds. From Fig. 1 it follows that the required $C_{n\beta,\min}$ values progressively reduce with a decrease in size. Thus, the smaller a bird, the lesser the required restoring yaw capability, allowing a decrease in $C_{n\beta,\min}$. This means that aerodynamic wing features which efficiently augment yaw stability become less important so that simpler wing forms can provide the required $C_{n\beta,\min}$. Thus, even wing forms similar to a rectangle may be efficient enough in generating the required stabilizing yawing moment.

The results presented in Figs. 6 and 7 show by comparison with the data depicted in Fig. 1 that the $C_{n\beta}$ values which the two wing forms (wing with slotted tips as well as wing with sweep at its outer part) can generate are considerably larger than the required minimum given by $C_{n\beta,\min}$. This holds for the entire lift coefficient range, and the surplus is particularly pronounced at higher C_L values because there is a progressive increase of $C_{n\beta}$ with C_L whereas $C_{n\beta,\min}$ shows only a linear one. To sum up, it can be concluded from the comparison of Figs. 6 and 7 with Fig. 1 that the wing alone can provide the required yaw stability (static and dynamic) so that no vertical tail is needed.

Dutch Roll Damping and Related Requirements on Aerodynamic Moment Characteristics

An appropriate relation for describing the damping of the Dutch roll is ζ_d which is approximately given by the expression in Eq. (4). This expression shows that ζ_d is dependent on the yaw rate derivative C_{nr} which is one of the aerodynamic functions of the vertical tail. The question is whether an adequate Dutch roll damping can be achieved for the aerodynamic configuration without a vertical tail, alone by the wing.

An appropriate damping level of the Dutch roll, including prevention of unacceptable overshooting characteristics, can be attained by imposing a lower limit on ζ_d:

$$\zeta_d \geq \zeta_{d,\min} \tag{9}$$

With introduction of $\zeta_{d,\min}$, a lower bound can be obtained for C_{nr} such that

$$|C_{nr}| \geq |C_{nr}|_{\min} \tag{10}$$

The minimum $|C_{nr}|_{\min}$ can be derived from Eq. (4) by substituting for ω_{nd} and accounting for the lift equation which is given for small flight path angles $|\gamma| \ll 1$ (covering horizontal and gliding flight) by

$$C_L(\rho/2)V^2 S = mg\cos\gamma \approx mg \tag{11}$$

Thus, $|C_{nr}|_{\min}$ can be expressed as

$$|C_{nr}|_{\min} = 2\frac{i_z}{s}\sqrt{\mu C_{n\beta}}\zeta_{d,\min} \tag{12}$$

From scaling law relations ($Ss \sim m$) it follows that the relative mass parameter $\mu = 2m/(\rho S s)$ can be regarded as approximately independent of the size of birds. Furthermore, it is here again assumed that the ratio i_z/s does not depend on the size. It follows then from Eq. (12) that $|C_{nr}|_{\min}$ decreases with a reduction in size according to the decrease of $\sqrt{C_{n\beta}}$. Thus, the requirements on the aerodynamic damping derivative C_{nr} are basically reduced for smaller flying objects like birds and miniscale airplanes.

From an aerodynamic point of view, there is another interesting result concerning the required minimum damping $|C_{nr}|_{\min}$. This relates to the fact that $|C_{nr}|_{\min} \sim \sqrt{C_{n\beta}/C_L^2}$, Eq. (12). There are wing forms [7] for which $C_{n\beta} \sim C_L^2$. In these cases, the ratio $C_{n\beta}/C_L^2$ is constant, independent of the flight condition (lift coefficient or speed, respectively). It is determined only by the geometric properties of the wing, such as aspect ratio or sweep. As a result, the required damping would be constant for a given aerodynamic configuration, showing no change with the lift coefficient or speed, respectively.

According to the dependency of $|C_{nr}|_{\min}$ on $C_{n\beta}$, its lowest acceptable value is obtained for $C_{n\beta} = C_{n\beta,\min}$. Denoting this value by $|C_{nr}^*|_{\min}$, it can be expressed as

$$|C_{nr}^*|_{\min} = 2\frac{i_z}{s}\sqrt{\mu C_{n\beta,\min}}\zeta_{d,\min} \tag{13}$$

Using this relation, an insight into the required magnitude of the aerodynamic damping can be obtained. Here again, the experience with airplanes dynamics in the yaw axis may be used, providing data on required Dutch roll damping characteristics. For specifying $\zeta_{d,\min}$, reference is made to existing flying qualities requirements [12,13]. There are values ranging from 0.08 to 0.4 depending on aircraft class and flight phase category. A value of $\zeta_{d,\min} = 0.1$ is selected for the present investigation. Furthermore, a value of $i_z/s = 0.22$ is again applied. For the relationship between the wing area and mass, the expression $S = 0.1576m^{0.722}$ is used as a scaling relation, with reference made to . Results from an evaluation of Eq. (13) with the described data are shown in Fig. 8. From these results, it basically follows that the required value of the aerodynamic damping derivative is rather small. It reduces with a decrease in the mass or size of the flying objects.

The most important result from the data shown in Fig. 8 is again, that the lowest acceptable aerodynamic damping moment can be provided by the wing alone. This is confirmed with data presented in Fig. 9 which shows the aerodynamic damping derivative C_{nr} for unswept wings. For determining the data presented in Fig. 9, reference was made to [8]. Comparison with Fig. 8 shows that the

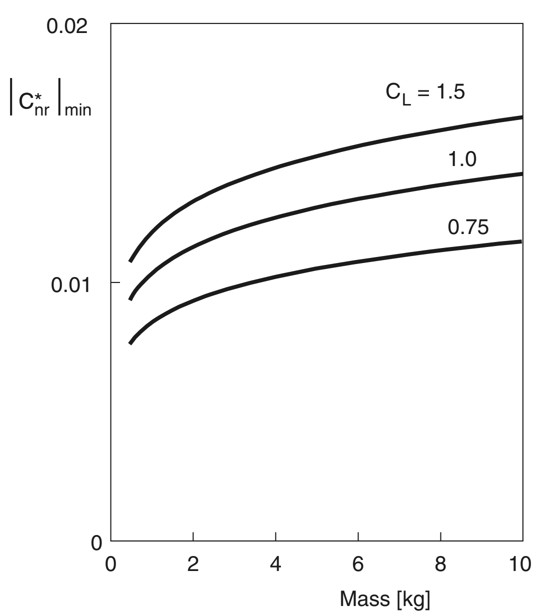

Fig. 8 Estimation of required aerodynamic yaw damping moment.

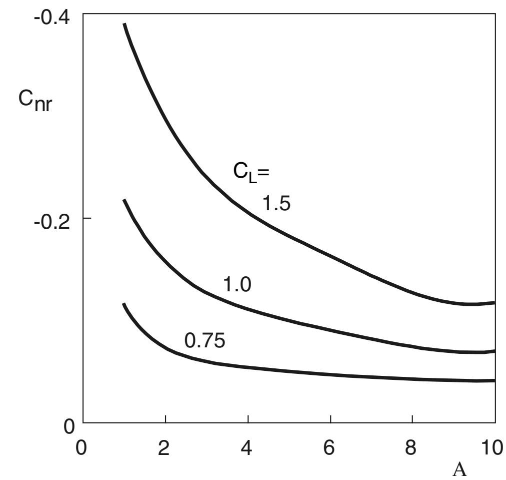

Fig. 9 Estimated yaw damping derivative of unswept wings.

damping derivatives of the wing can considerably exceed the required minimum level.

Spiral Mode

For the spiral mode, which is a slow mode of motion showing an aperiodic behavior, the effect of the tail manifests in the ratio $C_{nr}/C_{n\beta}$, Eq. (5). This quantity is combined with the derivatives $C_{l\beta}$ and C_{lp}. Generally, the ratio $C_{nr}/C_{n\beta}$ is negative for configurations with a vertical tail as well as for those employing only a wing. The derivative C_{lp} is negative, whereas $C_{l\beta}$ can show different signs. For straight or swept-back wings, as well as for those with dihedral, $C_{l\beta}$ is negative. Then, the effect of $C_{nr}/C_{n\beta}$ exerts a stabilizing influence on the spiral mode. This basic result holds for configurations with a vertical tail as well as for wing-alone configurations.

An interesting aspect of the spiral mode relates to the fact that a certain degree of instability can be accepted from an aircraft flying qualities point of view. This is basically due to the slowness of the spiral mode. There are flying qualities requirements which recommend acceptable values or specify admissible limits of instability [12,13]. Minimum values for time to double amplitude amount to 12 or 20 s, depending on flight phase category. With this background in mind and considering the fact that the ratio $C_{nr}/C_{n\beta}$ is of partial influence, the effect of the vertical tail is considered to be of reduced importance in regard to the spiral mode when compared with its relevance for the Dutch roll.

Control and Trim in Asymmetrical Flight

The vertical tail in airplanes provides yawing moments for control and trim of asymmetrical flight conditions. These flight conditions include 1) takeoff in crosswinds, 2) landing in crosswinds, and 3) asymmetrical external loads.

Takeoff in Crosswinds

With regard to takeoff of airplanes in crosswinds, a yaw control capability is basically required for the ground-roll on the runway. A control deflection of the rudder at the vertical tail compensates for the yawing moment generated by the sideslip angle which is caused by the crosswind. Such a necessity does not exist for birds which need no runway for takeoff. Birds, which require some distance for running before takeoff, may be able to avoid a crosswind by choosing a favorable direction against the wind.

Landing in Crosswinds

With regard to landing of birds in crosswinds, they can basically make use of a technique showing a crab angle relative to the flight direction. Thus, they can approach the landing place without the necessity of a yaw control capability. Furthermore, they can select a wide range of approach directions because they are landing on a spot and there is no runway determining a fixed direction. They can even avoid an approach in a crosswind condition by selecting a direction against the wind if there are no obstacles preventing this. In such a case, it is possible to perform a favorable headwind approach for which the ground speed is reduced.

Asymmetrical External Loads

An asymmetrical flight condition is due to an asymmetrical external load yielding a yawing moment. This is an issue for airplanes as well as for birds, Fig. 10. For dealing with an asymmetrical load of an airplane, a yaw control capability is usually required which is given by the rudder so that a vertical tail is needed. However, there is also another possibility for yawing moment balance without the necessity of a vertical tail. Such a possibility, described in the following, may be used by birds.

An asymmetrical external load basically produces a yawing moment because of the lever arm of its drag, Fig. 11. This yawing moment can be balanced by an opposing moment due to sideslip, yielding the following relation for yawing moment equilibrium (in nondimensional form)

$$(y_{\text{Load}}/s)C_{D,\text{Load}} + C_{n\beta}\beta = 0 \tag{14}$$

where $C_{D,\text{Load}} = 2D_{\text{Load}}/(\rho V^2 S)$ is the drag coefficient of the asymmetrical external load.

Because the asymmetrical external load additionally causes a rolling moment and the sideslip angle can also lead to a rolling moment (which may be an effect of wing sweep or dihedral), a roll control moment is required for equilibrium in the roll axis. Birds have the capability for roll control moments by rotating one wing half or both, and/or by twisting the horizontal tail. The rolling moment equilibrium can be formulated as

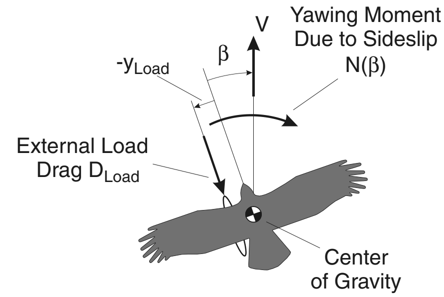

Fig. 11 Yawing moment balance in flight condition with asymmetrical external load.

$$\frac{y_{\text{Load}}}{s}\,\frac{m_{\text{Load}}g}{(\rho/2)V^2 S} + C_{l\beta}\beta + C_{l\delta a}\delta_a = 0 \tag{15}$$

where m_{Load} is the mass of the external load and $C_{l\delta a}$is the effective rolling moment control derivative. In the case that $C_{n\delta a}$ is not negligible, an additional contribution $\Delta C_n = C_{n\delta a}\delta_a$ to the yawing moment balance may be included in Eq. (14).

The relations given by Eqs. (14) and (15) can be solved to yield the required roll control deflection and the associated sideslip angle. As a result, a roll control capability which birds possess can be sufficient to deal with the yawing moment due to an asymmetrical external load. In this case, a yaw control capability is not required and, thus, there is no need for a vertical tail to cope with the asymmetrical external load.

a) Printed with permission by S. Morsch

b) Printed with permission by M. Siebert

Fig. 10 Birds with asymmetrical external load. (Courtesy of a) S. Morsch and b) M. Siebert.)

Adverse Yaw

Adverse yaw is an issue directly related to the ailerons and indirectly to the rudder. Basically, an aileron deflection generates not only a rolling moment, but also a yawing moment. For the case under consideration (adverse yaw), the yawing moment causes the airplane to yaw initially in a direction opposite to that desired by the pilot when exerting a roll command for a turn. If the adverse yaw effect is too large, an opposing yaw control deflection in terms of cross-coupled controls can be applied to achieve a yawing moment compensation. For this purpose, a vertical tail with a rudder for yaw control would be necessary.

Aerodynamic configurations without a vertical tail have to rely on other mechanisms if the adverse yaw effect is too large [18]. One approach is to use differential deflections of the ailerons. This means that the angle of the downward deflected aileron is smaller than that of the upward deflected one. Other possibilities for coping with adverse yaw is to apply Frise ailerons or to use spoilers in coordination with ailerons.

Use of Configurations Without Vertical Tail for Miniscale Airplanes

The preceding treatment about the fact that birds need no vertical tail basically holds also for miniscale airplanes, the size of which is considered to range from configurations comparable with large birds having wing spans of about 3–4 m to micro air vehicles the dimension of which is less than 15 cm in length, width, or height [10]. The main reason is that the scaling related to the square/cube law is basically valid also for this type of airplane. According to this law, the following relationship between the wing and the mass for changes in size applies

$$S = k_S m^{2/3} \tag{16}$$

where k_S is a constant. From Eq. (16), it follows that the wing loading changes with mass according to

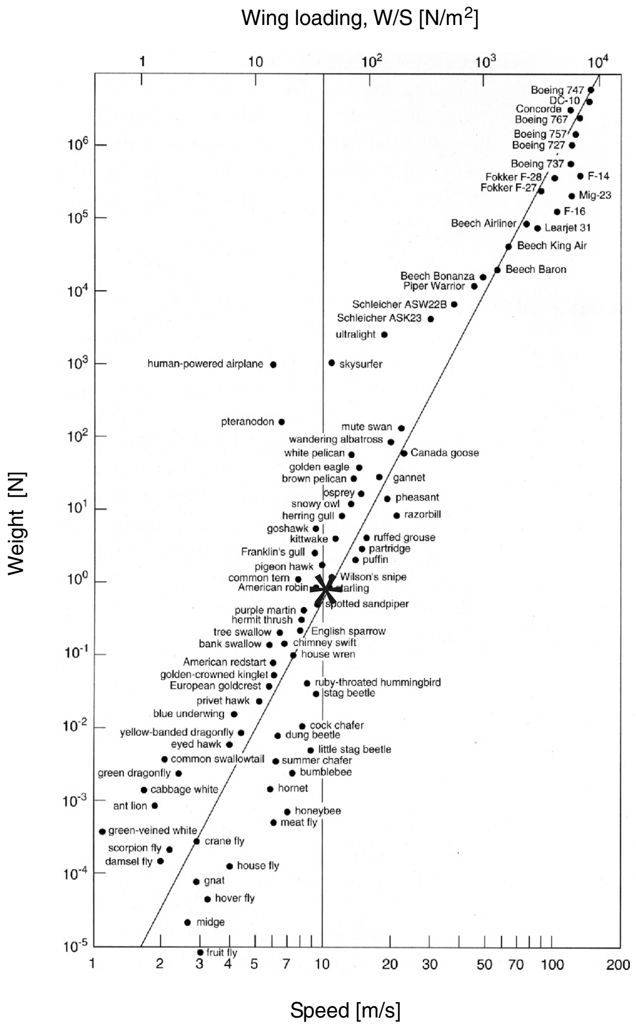

Fig. 12 Variation of wing loading with weight, micro air vehicle configuration denoted by star symbol (modified from [21,22]).

$$\frac{m}{S} = \frac{1}{k_S} m^{1/3} \tag{17}$$

An evaluation of this relation is graphically presented in Fig. 12, covering a wide range of flying objects. The evaluation also includes micro air vehicle data which fit well into the presented material.

The results on birds described in the preceding sections can be used for miniscale airplanes such that aerodynamic configurations are possible which need no vertical tail. According to these results, the abandonment of a vertical tail can be compensated for by a wing design showing appropriate features to generate the required levels of $C_{n\beta}$ and C_{nr}.

With respect to static and dynamic yaw stability, an adequate wing feature to augment $C_{n\beta}$ and, thus, ω_{nd} is sweep. In a similar manner as with bird wings treated in a preceding section, sweep in wings of miniscale airplanes can be used to increase $C_{n\beta}$. Sweep may be introduced for a part of the wing (preferably at the outer part because of its higher efficiency) or for the complete wing. The effect of wing sweep on $C_{n\beta}$ is shown in Fig. 13 which presents results of a generally valid nature from theory and experiments [19,20,23–25]. There is a significant increase of $C_{n\beta}$ due to sweep, holding for the entire aspect ratio range. This manifests also in the approximate formula for the effect of sweep [26]

$$C_{n\beta,\mathrm{sweep}} = \tan\varphi\left[\frac{0.5}{\cos\varphi} + \frac{1}{\mathrm{A}+4}\left(1 - \frac{1}{\cos\varphi}\frac{2\mathrm{A}}{\mathrm{A}+2}\right)\right]\alpha C_L \tag{18}$$

which shows how $C_{n\beta}$ progressively increases with the sweep angle. From the data presented in Fig. 13, it follows that this formula

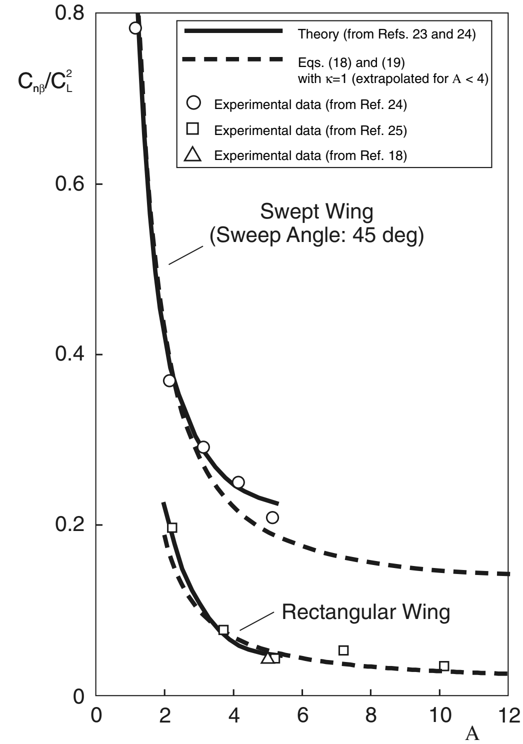

Fig. 13 Yawing moment due to sideslip of wings.

compares well with theoretical and experimental data, thus confirming the strong sweep effect as described by Eq. (18).

There is another interesting point which concerns wings without sweep. The results presented in Fig. 13 show that even this wing form yields a stabilizing yawing moment $C_{n\beta} > 0$. For small aspect ratios, $C_{n\beta}$ of unswept wings can reach a considerable magnitude. This also manifests in the following approximate relation holding for wings without sweep [26]

$$C_{n\beta} = \left(\frac{\kappa}{\mathrm{A}} + 0.168\frac{\mathrm{A}}{\mathrm{A}+2} - 0.1\right)\alpha C_L \tag{19}$$

where κ is an empirical factor (with κ between 1 and 1.2). Figure 13 shows that this formula compares well with theoretical and experimental data and, thus, confirms the considerable magnitude of $C_{n\beta}$ in the range of small aspect ratios.

Concerning a reduction in the size of miniscale airplanes (e.g., toward the smallness of micro air vehicles), it is noteworthy that the required degree of wing sweep can be decreased for two reasons:

1) The required angle of wing sweep decreases with a reduction in size. This is because the required yawing moment in terms of $C_{n\beta,\min}$ reduces with the decrease in the size of the vehicle, basically according to the relationships presented in Fig. 1.

2) The required sweep angle for an adequate level of static and dynamic yaw stability also reduces with a decrease in the aspect ratio of the wing. This manifests in the results presented in Fig. 13. There is a significant increase of $C_{n\beta}$ with a reduction in the aspect ratio, holding for rectangular as well as for swept wings. The increase of $C_{n\beta}$ with a reduction in the aspect ratio is of interest for miniscale airplanes because they may show rather small values.

With regard to yaw damping characteristics, the size of the vehicle and the aspect ratio have an impact here, too. This concerns the required yaw damping level in terms of $|C_{nr}|_{\min}$ as well as the available yaw damping C_{nr} which the wing can generate. The size effect manifests in relationships as presented in Fig. 8. There is a reduction of the required aerodynamic damping derivative in terms of $|C_{nr}^*|_{\min}$. A decrease in the aspect ratio also contributes to an improvement of the damping relationship because it yields an increase of the C_{nr} values which the wing can generate. This is shown in Fig. 9 which depicts results on unswept wings.

Conclusions

The vertical tail is a component of the aerodynamic configuration of airplanes which can be found with any type of vehicle. In contrast, there is no bird which possesses a vertical tail. Lacking of the vertical tail in birds contrasts with the fact that they have in common with airplanes the other components of the aerodynamic configuration, i.e., the wing, the body, and the horizontal tail.

With reference to the functions which the vertical tail has to furnish, the unique relationships for the flight mechanics of small flying objects, like birds and miniscale airplanes, and for the related aerodynamic configurations are considered. It is shown that the wing can take over these functions in the case of small flying objects such that a vertical tail is not needed. The functions concern yaw stability (static and dynamic) and damping, as well as control and trim of asymmetric flight conditions. Aerodynamic configurations needing no vertical tail are an issue which is of relevance for technical applications. From the characteristics of birds, it can be learned how such configurations and the related benefits may be used for airplanes. This is of particular significance for miniscale airplanes which are comparable in size with birds. The size of such airplanes is considered to range from configurations showing wing spans of about 3–4 m to micro air vehicles the dimension of which is less than 15 cm in length, width, or height.

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