Aerobasics – An Introduction to Aeronautics

6. Airfoils and Wings in Subsonic Flow

S P Govinda Raju

This part of the article continues the discussion of the aerodynamic characteristics of airfoils presented in the previous part and extends it to wings at subsonic speeds. The effects of high-lift devices and spoilers are considered and their application indicated. The effects of wing sweep and finiteness of aspect ratio are analyzed.

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1. Introduction

In the early days of airplane development, airfoils were developed by cut and try methods. Airfoils suitable for airplanes and propellers of that time were for operation at moderate Reynolds numbers of 10^6-10^7 and at low Mach numbers below 0.5. The methods of construction at the time did not permit a very smooth surface finish for the wings. Successful airfoils developed at that time performed adequately over the above operating conditions. Over time, the development of airplanes has been in the direction of larger size, higher speed and better construction and finish. Thus, the operating envelope of airplanes includes higher Reynolds numbers up to 10^9 and Mach numbers up to 0.85 for civil aircraft and up to about Mach 2 for combat aircraft. Airfoils better suited for these conditions have been developed using new theoretical knowledge of compressible flows and boundary layers.

We shall generally discuss the low speed ($M < 0.5$) characteristics of airfoils. With some qualifications, these discussions also apply to wings of moderate to large aspect ratio. Flight conditions of most airplanes during landing and take-off lie in this domain. Thus, the discussions below apply to these flight conditions.

Keywords
Flap, spoiler, wing sweep, aspect ratio, induced drag, downwash.

2. Low Speed Characteristics of Airfoils

Theoretical and computational methods are now available for predicting the aerodynamic characteristics of airfoils. Some general conclusions about airfoil characteristics can be derived from the theoretical methods. For all useful airfoil sections in the range of 6–20% thickness, the lift curve slope (rate of change of lift coefficient with incidence in degrees) is about 0.1 per degree and increases slightly with thickness. The aerodynamic centre of the airfoil is at a distance of about 0.25 chord from the leading edge. The thickness of the airfoil affects the maximum lift coefficient to some extent. A thin airfoil stalls early due to flow separation near its relatively sharp leading edge. A very thick airfoil stalls due to flow separation on the top surface near the maximum thickness point. The most favorable situation occurs in the range of thicknesses around 12–15%. The separation point is closest to the trailing edge under this condition. The camber of the airfoil plays an important role. It strongly affects both the lift at zero incidence and the moment about the aerodynamic centre. A camber of a few percent has a favorable effect on drag and maximum lift coefficients.

Figure 1 shows the aerodynamic characteristics of three airfoils of progressively increasing camber. The symmetrical airfoil, section A, has a low drag coefficient for

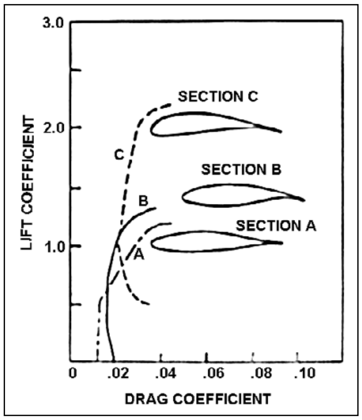


Figure 1. Comparison of aerodynamic performance of airfoils. A symmetrical airfoil, section A, has a low drag coefficient at lift coefficient values from zero to around 0.5. The section B, with a moderate amount of camber, has low drag coefficient values in the lift coefficient range of 0.5 to 1.0. The section C, with a large camber, has low drag coefficient values in the lift coefficient range of 1.0 to 2.0. Thus, one may select the section of an airfoil for a specific application depending on the operating lift coefficient range.

small values of the lift coefficient below 0.4. The airfoil with maximum camber, section C, has a relatively high drag coefficient at this lift coefficient while its drag coefficient is lower near the maximum lift coefficient. The airfoil with moderate camber, section B, has a lower drag coefficient in the range of operating lift coefficients (0.4–1.0) and is more suitable for an aircraft wing. During take-off and landing, the maximum lift coefficient can be increased by the use of trailing edge flaps and leading edge devices (slats) which will only be deployed during these phases of flight.

3. Flaps, Slats and Spoilers

A flap is a segment of an airfoil near its trailing edge hinged so that it can be deflected relative to the main body of the airfoil. *Figure* 2 inset shows a typical airfoil with a simple flap. Deflecting the flap changes the lift coefficient of the airfoil at any given incidence as in the figure. The control surfaces of an airplane (the elevator, the rudder and the aileron) are actually flaps associated with the appropriate aerodynamic lifting surfaces (the horizontal tail, the vertical fin and the main wing respectively). Change in lift coefficient on the relevant

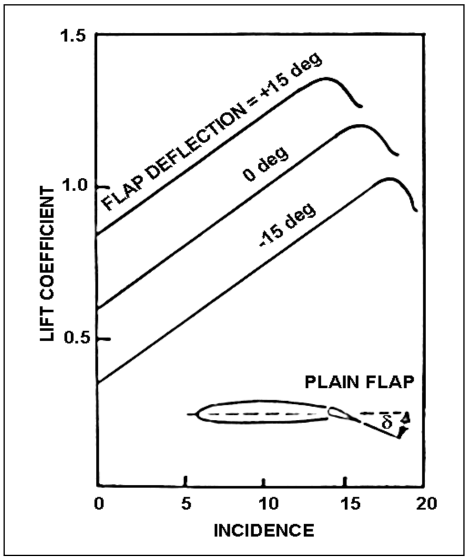


Figure 2. Effect on lift coefficient due to the deflection of a plain flap. Deflection of a plain flap on an airfoil at a given incidence changes its lift coefficient roughly in proportion to its deflection over a range of about ±30 degrees. Thus, it is useful as a control device to vary the lift of a wing without changing the incidence.

lifting surface due to a control surface deflection induces a moment about the relevant axis of the airplane. The moment is nearly proportional to the flap deflection. For increasing these control moments, the control surfaces have to be located as far as possible from the centre of gravity of the airplane. This dictates the locations of the control surfaces.

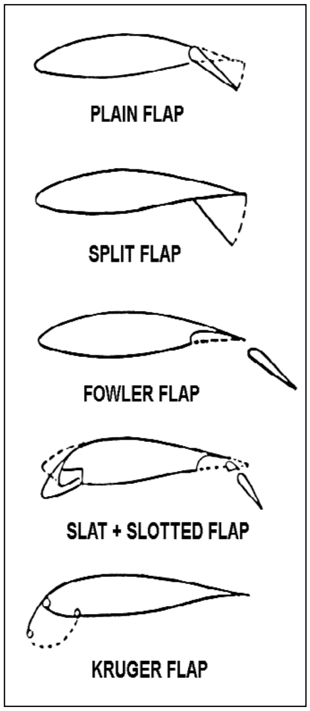


Figure 3. Typical configurations of high-lift devices. The maximum lift coefficient of an airfoil can be increased by using various types of flaps and slats (leading edge devices). The flaps increase the lift coefficient of an airfoil at the same incidence while slats delay stall.

In the interest of safety and to minimize the runway length required, an airplane takes off and lands at a relatively lower speed in relation to its normal flight speed. To generate adequate lift under these flight conditions, it has to operate at a relatively high value of the lift coefficient. A flap is generally used for enhancing the lift coefficient under these conditions. Different types of flaps of varying effectiveness and corresponding complexity in deployment have been developed for this purpose. *Figure* 3 shows a few types of flaps. Simple flaps enhance C_L by about 0.8. A more complex flap in combination with a slat (leading edge flap) leads to a maximum lift coefficient enhancement of over 1.6. It is relevant to point out here that a trailing edge flap increases lift at any incidence but reduces the incidence at stall while a slat delays stall (which thus occurs at a higher incidence). The combination of slat and flap leads to a large enhancement of C_L at nearly the same incidence and this is a valuable feature as it permits take-off and landing of an airplane with only minor changes in attitude. This feature is illustrated in *Figure* 4. Slats and flaps are commonly used on large civil transports and combat aircraft. It may be noted here that there is an increase in the drag coefficient associated with the higher lift coefficient while using the flap. Full lift enhancement possible with flaps can be used during landing. However, flap deflection is always limited during take-off to meet the take-off climb requirement with net thrust (thrust minus drag), which suffers a reduction due to the higher drag coefficient.

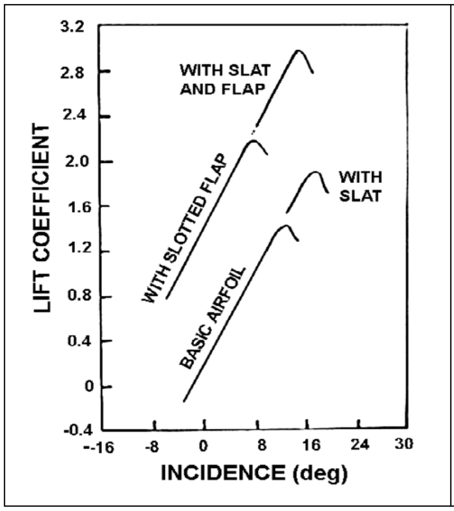


Figure 4 (left). Combination of a slat and a flap for a high lift coefficient.The combined use of a flap and a slat results in a large increase in maximum lift coefficient with only a minor change in incidence. This feature is valuable as it minimizes the change in attitude of an airplane during take-off or landing.

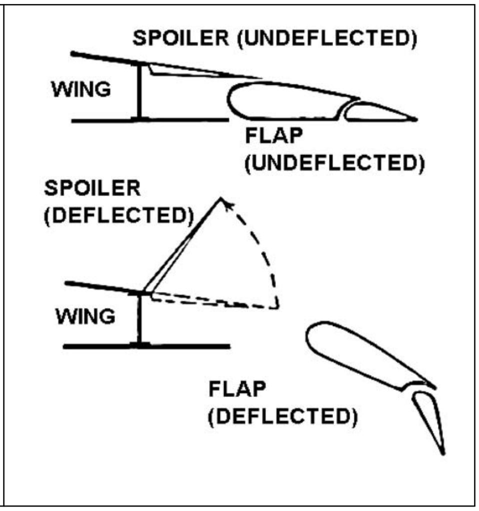


Figure 5 (right). Typical installation of a flap and a spoiler on a wing.The flap and the spoiler can be deflected independently. During landing, the spoiler is undeflected but the flap is fully deflected. On landing, the spoiler is deflected to reduce lift and increase drag.

A spoiler when deflected spoils the flow on the top surface of a wing and reduces lift. It is illustrated in *Figure* 5. Spoilers are useful for dumping lift just after landing so that the weight of the airplane is immediately transferred to the wheels. This enhances the controllability of the airplane on the ground. Further, as the use of spoilers increases drag, it also reduces the landing distance. Spoilers are also useful as control surfaces. Spoilers are often used as ailerons by deflecting them on only one half of the wing. When symmetrically deployed (on both sides of the wing), a small deflection of the spoilers increases drag and can be used for controlling the rate of descent of airplanes on approach to a landing field. Speed brakes are similar to spoilers but are mounted on the fuselage of combat aircraft. They are useful in quickly reducing flight speed as well as in preventing excessive build-up of speed in a dive.

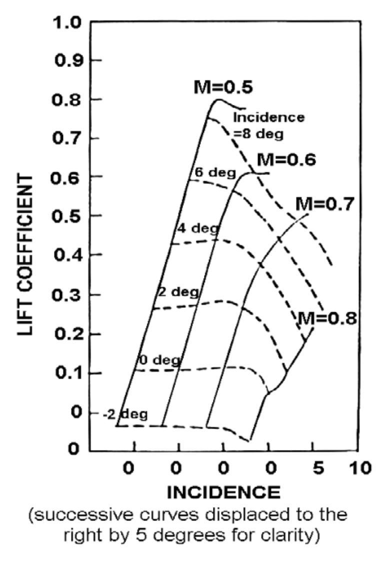
4. Compressibility Effect

An airfoil in a flow generates lift largely due to the lowering of pressure on the top surface of the airfoil relative to free-stream static pressure. At a low flight Mach number, this lowering of pressure leads to only an insignificant reduction in density. However, as the flight speed increases, the reduction in the density becomes significant and to compensate, the flow velocity increases and leads to an additional fall in pressure. Thus, there is a small increase in lift coefficient over the value in incompressible flow, C_{Li}, and is given by the Prandtl–Glauert rule:

$$C_{\mathrm{L}} = \frac{C_{\mathrm{L}}}{\sqrt{1-\mathrm{M}^2}}. \tag{1}$$

Here M is the free-stream Mach number, V/a_∞, where a_∞ is the speed of sound in the free stream.

As the free-stream velocity is increased further, the local velocities on the top surface of the airfoil increase until at a free-stream Mach number of M_{CR} (the critical Mach number), the local velocity at some point reaches sonic speed ($\mathrm{M}_{\mathrm{L}} = 1$). A further increase in free-stream velocity leads to local supersonic flow with shocks. The interaction of shocks with the boundary layer on the airfoil causes flow separation. This leads to a loss of lift and increase of drag. For a typical airfoil, M_{CR} is in the region of 0.7–0.8. *Figures* 6 and 7 show the typical variation of C_{L} and C_{D} with Mach number for a



(successive curves displaced to the right by 5 degrees for clarity)

Figure 6 (left). Effect of Mach number on the lift coefficient.The lift coefficient of an airplane configuration is practically unaffected up to a Mach number of about 0.5. Beyond this, there is a rapid reduction in the value of maximum lift coefficient.

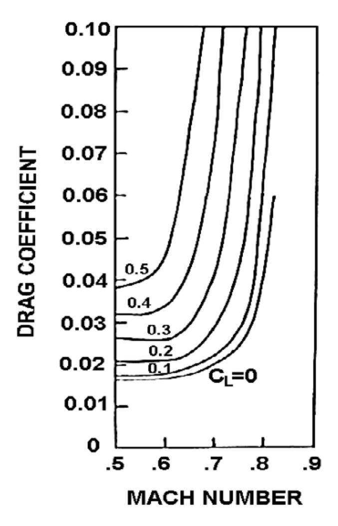


Figure 7 (right). Effect of Mach number on the drag coefficient. The drag coefficient of an airplane configuration is practically unaffected up to a Mach number of about 0.5. Beyond this, there is a rapid increase in the drag coefficient particularly at large values of the lift coefficient.

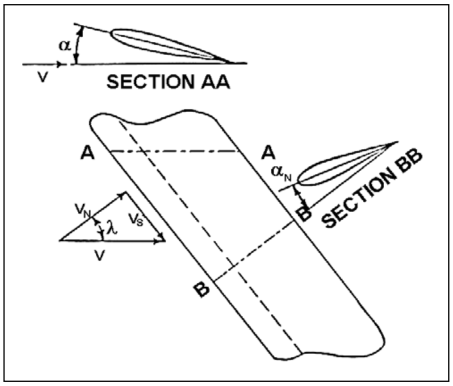


Figure 8. Effect of sweep on an airfoil. The free-stream velocity has a component V_N normal to the leading edge and V_S parallel to it. The component V_S does not have a significant effect on the flow. The forces on the airfoil are primarily determined by V_N.

conventional subsonic airplane configuration. The figures clearly illustrate the phenomenon of loss of lift and rapid rise in drag coefficient at a Mach number around 0.7. Airplanes using conventional airfoils are thus limited to a flight speed of less than about M = 0.7. The critical Mach number of an airfoil depends on its thickness. A larger thickness implies higher local flow velocities and thus a reduced critical Mach number. Thus, some increase in flight speed is possible if one uses a very thin airfoil profile for the wing. However, this leads to a weight penalty, as a thinner wing has to have a thicker skin to withstand the flight loads.

One can delay the adverse affects of compressibility to a significant extent by using wing sweep. *Figure* 8 shows an airfoil set at a sweep angle Λ, defined as the angle between the longitudinal axis of the airfoil and the normal to the free stream. The free-stream velocity has a component $V_{\mathrm{N}} = V \cos \Lambda$ normal to the airfoil axis and a component $V_{\mathrm{S}} = V \sin \Lambda$ along the axis. Inviscid theory indicates that the component V_{S} has no effect on the aerodynamic forces, which are completely determined by V_{N}. The flow corresponds to that on an unswept airfoil in a flow of free-stream Mach number M cos Λ. Thus, the critical Mach number is enhanced to a higher value by a factor $1/\cos \Lambda$.

It may also be noted that the lift per unit span of the airfoil corresponds to a free stream of velocity $V \cos \Lambda$

Box 1. Merits and Demerits of a Swept Wing

For flight at Mach numbers up to about 0.6, a straight (unswept) wing is very suitable. For flight at a higher Mach number, it is possible to use a straight wing with a reduced wing thickness ratio to increase the critical Mach number to a higher value than the cruise speed. But for economic reasons, civil aircraft try to cruise at Mach numbers around 0.8 to 0.85. A straight wing for cruise at these speeds would be extremely thin with a mean wing thickness ratio* around 8%. Such a wing will be very heavy, as a thin wing needs a very thick skin to withstand the bending loads on the wing during flight. Use of wing sweep of about 25–35 degrees permits the use of a much thicker wing (with a stream-wise thickness ratio around 10–13%) with thinner skins and such a wing will be lighter in spite of the fact that a swept wing of a given span is longer along the wing axis. Further, the capacity of the wing as a fuel tank is much increased and this is useful. The swept wing also leads to a better layout for the installation of main landing gears contributing to further weight reduction. Most civil jets therefore use swept wings (with a sweep angle of about 25–35 degrees) with carefully designed airfoil profiles which maximize the critical Mach number.

A highly swept wing, often used on combat airplanes, has some disadvantages. It was pointed out above that a swept airfoil has a lower lift curve slope than an unswept airfoil. The difference becomes larger as the sweep angle is increased. Thus a highly swept wing needs a larger incidence for flight. As an illustration, the incidence required for maximum lift coefficient on a wing with 60degrees sweep is over 30 degrees. An airplane cannot reach an incidence of over about 15 degrees during take-off or at landing due to the rear end of the airplane scraping the ground. Thus, full advantage cannot be taken of the lifting capacity of the wing during take-off and landing. There may also be a problem with visibility of the runway from the cockpit as the airplane is in a nose-high attitude. This was the case with the Concorde airplane, which solved the problem using a nose section, which drooped down during take-off and landing.

The aerodynamic effect of sweep discussed above is also obtained with a wing which is swept forwards rather than backwards as above. A swept forward wing is prone to aero-elastic problems because the wing twist due to aerodynamic loads enhances the local incidence. To counter this, a stiffer wing is required and this tends to be heavier. It is seldom used. In a swept back wing, which is preferred, the wing twist due to aerodynamic loads reduces the incidence near the tips.

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* Airplane wings are generally thicker near the root as compared with the tips for minimizing weight. The wing thickness ratios indicated are average values over the wingspan.

and is thus reduced by the factor cos $^2\Lambda$ as lift is proportional to the square of the speed. However, the incidence relative to airfoil axis along its span α_{N} is larger than the incidence defined relative to the axis normal to free stream α by the factor cos Λ. Thus for the same α, the lift of the airfoil drops only by a factor cos Λ. Thus, the lift curve slope of a swept airfoil is lower than that of an unswept airfoil by this factor.

Experiments confirm the above analysis on the effect of sweep qualitatively. The actual gain in critical Mach number, while significant, is somewhat less than the theoretical value.

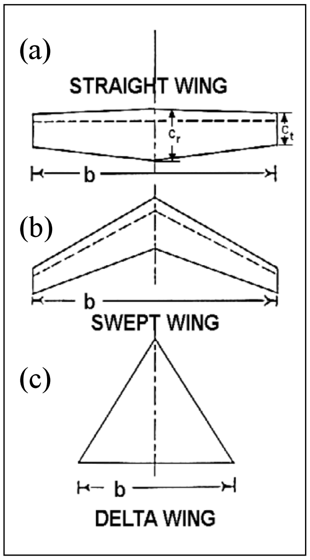

Figure 9. Typical plan forms for airplane wings. The straight wing (a) is well suited for M < 0.5. The swept wing (b) delays the effects of compressibility and can be used for higher Mach numbers. The delta wing (c) is a special case of (b) and is often used on combat aircraft.

5. Performance of Wings

A wing is a lifting surface of finite size. The aspect ratio of a wing defined as the ratio of the square of span to plan form area is an indication of this. The aspect ratio of wings generally varies in the range of about 2 to 15. Wings can be of different plan forms as illustrated in *Figure* 9. They are symmetrical about a stream-wise axis. A typical stream-wise cross-section of a wing is an airfoil at some angle relative to a reference plane. This angle is called the setting and is a constant over the span for an untwisted wing. For a twisted wing, this setting varies along the span-wise direction. Further, the chord of the wing at the middle of span, (the root chord) is generally larger than the chord at the wing tip (the tip chord). The ratio of tip chord to root chord, the taper ratio, is generally around 0.3–0.4.

The aspect ratio, taper ratio and twist all have significant effects on the way the lift is distributed over the span of the wing and on induced drag, which is explained in the next section. A small aspect ratio wing permits a large roll rate and is required for combat airplanes. However, it leads to a large induced drag. A high aspect ratio wing has low induced drag and is preferred for use on transport airplanes

The taper of the wing is very helpful in reducing wing weight. However, as the taper ratio is reduced, the wing shows an increasing tendency towards tip stall. As the incidence of a wing is increased, the stall of a wing begins at some span-wise location and spreads with further increase of incidence. If the stall begins near the tips first, it is called tip stall and this is undesirable because it affects the flow around the ailerons and thus leads to loss of roll control. This can be avoided by reducing the local incidence of the wing sections near the tips by using wing wash out (reducing the wing setting near the tips).

6. Induced Drag

The concept of induced drag can be explained by an approximate analysis originally due to Max Munk and is given below.

A wing generates lift by imparting downward momentum to the stream of air passing around it. This downward momentum is largely confined to a downstream region with the wingspan as diameter. The actual distribution of momentum in this region is complex. The flow consists primarily of two vortices placed almost a span apart with their axes aligned with the flow direction (called the trailing vortices). One may grossly approximate this flow as in *Figure* 10. In spite of the approximation, the results of this analysis are substantially correct and can be justified by a more complete analysis. In this approximation, the wing deflects the fluid flowing through the circular area normal to the stream direction with a diameter equal to wingspan. The downward velocity in this region is called the downwash and reaches an average value, w, far downstream of the wing. The downward flux of momentum due to this downwash is

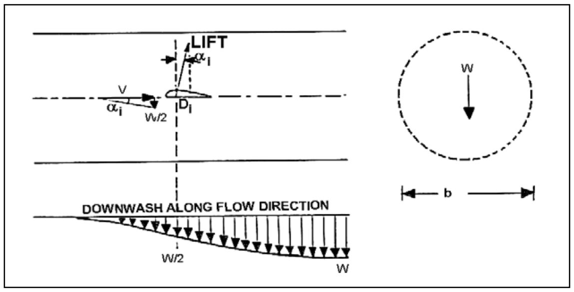

Figure 10. Idealized flow due to a wing.A wing develops lift by deflecting downwards a stream of fluid with its span as diameter. This results in a downward component of velocity, the downwash. The kinetic energy associated with the downwash constitutes a loss of mechanical energy and is reflected as the induced drag of the wing.

equal to the wing lift as

$$L = \rho V (\frac{\pi b^2}{4}) w. \tag{2}$$

Therefore

$$w = \frac{4L}{\rho V \pi b^2}. \tag{3}$$

The downwash at the wing location is half this value and it deflects the free stream at the wing by an angle $w/2V$. The lift vector, which is normal to the deflected stream direction, has a component in the original stream direction

$$D_{\mathrm{i}} = \frac{Lw}{2V} = \frac{2L^2}{\rho V^2 \pi b^2}. \tag{4}$$

This component is called induced drag and is an addition to the drag of the airfoil section (profile drag) integrated over the span. It can be written in dimensionless form as

$$C_{\mathrm{Di}} = \frac{C_{\mathrm{L}}^2}{\pi A}. \tag{5}$$

Here, A is the aspect ratio of the wing defined as the span squared divided by the wing area. C_{Di} is the coefficient of induced drag.

Downwash of a wing persists for a long distance (some miles) behind a wing and is dissipated slowly due to viscosity. A small airplane flying into the downwash field of a large one will experience this as a heavy gust and this may be dangerous. Take-off of a small airplane from the same runway as a large one must be only after a suitable time delay for this reason.

Induced drag is due to the loss of kinetic energy in the downwash field.. It can be easily shown that the power expended by the wing in overcoming induced drag is exactly equal to the kinetic energy flux in the downwash flow.

Equation (4) shows that induced drag increases rapidly with span loading, L/b. Induced drag can thus be reduced by increasing the span b (or equivalently aspect ratio A). Transport aircraft use this principle to achieve a significant reduction in drag by using A as high as 12.

Induced drag depends inversely on the square of the flight speed and is thus larger at lower speeds. Thus it is more important under take-off and landing conditions as compared to cruise.

Larger values of A are not attractive as the wing weight increases with A and there is no net benefit.

It may be also be noted that in the region downstream of the wing there is a downwash as given by (3). The flow in this region is tilted downwards by an angle w/U. This is the downwash angle, ε, given by:

$$\varepsilon = \frac{4L}{\rho V^2 \pi b^2} = 2\frac{C_{\mathrm{L}}}{\pi A}. \tag{6}$$

Thus, when the wing incidence changes, there is a change in downwash which can be represented by

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\alpha_{\mathrm{w}}} = \frac{2}{\pi A}\frac{\mathrm{d}C_{\mathrm{L}}}{\mathrm{d}\alpha_{\mathrm{w}}}. \tag{7}$$

As a rough measure of this, we can take the lift curve slope $\mathrm{d}C_{\mathrm{L}}/\mathrm{d}\alpha_{\mathrm{w}}$ as 2π per radian which is the value for an airfoil. Then

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\alpha_{\mathrm{w}}} = \frac{4}{A}. \tag{8}$$

Taking a typical value of A to be 8, $\mathrm{d}\varepsilon/\mathrm{d}\alpha_{\mathrm{w}} = 0.5$. This is a surprisingly large value. Its importance lies in the fact that horizontal stabilizers of conventional airplanes are immersed in the downwash field of the main wing and their effectiveness in stabilizing the airplane in pitch depends on producing a lift as large as possible for a small change in wing incidence. It is seen that for a small rotation of the aircraft in pitch, $\Delta\alpha_{\mathrm{w}}$ the horizontal tail, being fixed to the body of the airplane which includes the wing, also deflects by the same angle. But the flow at the horizontal tail also turns by an amount $\Delta\varepsilon$ in the same direction thus reducing the incidence of the tail to $\Delta\alpha - \varepsilon$. This is less than $\Delta\alpha_{\mathrm{w}}$ (by about 50%). Thus, the stabilizing effect of the horizontal tail is reduced substantially and this needs to be taken into account in sizing the horizontal tail.

The above analysis also indicates the effect of downwash on the wing itself. It can be shown that the lift curve

Suggested Reading

[1] **Ira H Abbott and Albert E Von Doenhoff, *Theory of Wing Sections*, Dover Publications, Inc., New York, 1979.**

[2] **Robert T Jones, *Wing Theory*, Princeton University Press, Princeton, New Jersey, 1990.**

slope of a wing is less than that of an airfoil by a factor of $1/(1 + 2/A)$. Thus, wings of small aspect ratio often need a large incidence during flight. This problem was already considered above in connection with wing sweep, which also has a similar effect. The combined effect of high wing sweep and small aspect ratio needs to be dealt with in the same manner.

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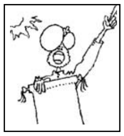

Information and Announcements

Nocturnal Pollination: Patterns and Processes

23 – 27 March 2009, Indian Institute of Science, Bangalore
Aimed at Young Indian Researchers at graduate, post-graduate, post-doctoral or lecturer level
(candidates in final year BSc to lecturer-level may apply).

The nocturnal realm is full of fascinating and as yet undiscovered phenomena. The aim of this workshop **(which is the first of its kind ever)** is to provide young researchers an opportunity to interact with an international group of resource persons and to bring together pollination ecologists, sensory biologists, behavioural ecologists and botanists to discuss plants, animal pollinators and their specialized nocturnal relationships. The workshop will encourage interdisciplinary interactions that make this research area so fascinating. The workshop will have a mixture of theory (evolution; historical, biogeographical and phylogenetic patterns; mechanisms i.e., processes) and practical demonstrations (e.g. sampling and analysis of plant volatiles, measurement of light spectral reflectance curves and ambient light levels, characterization of pollinator optics and olfaction, behavioural observation methods, experimental design and analysis).

Interested individuals may apply giving biodata (with date of birth), passport size photograph and full contact address including e-mail and fax (if available), nature of research work and/or teaching being undertaken, reasons for interest in the workshop and names of two referees to: Renee M Borges, Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560 012, India, Tel.: 080-2360 2972 or 2293 3103, Fax: 080-2360 1428.

Applications should be sent by email only to the following IDs [renee@ces.iisc.ernet.in and copy to sunitha@ces.iisc.ernet.in] with "**Application for Nocturnal Pollination Workshop**" as the Subject of the email. If applicants do not get an email acknowledgement of the receipt of their application within four days, they should send another email or call (this is to avoid applications being lost in cyberspace). The cost of return train fare and boarding and lodging in Bangalore will be borne by the Organisers.

Workshop Co-organiser: Almut Kelber, Vision Group, Lund University, Sweden. Workshop currently sponsored by: Swedish International Development Agency (SIDA), Department of Science and Technology (DST), Indo-US Science and Technology Forum (IUSSTF), Indian Institute of Science (IISc). For additional information visit: http://ces.iisc.ernet.in/renee;

Last date for receipt of applications is **15 February 2009.** Successful applicants will be notified by **24 February 2009.**