Aerobasics – An Introduction to Aeronautics

15. Mini and Micro Airplanes

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There is much current interest in small unmanned airplanes weighing about five kilograms all the way down to about 100 grams. Even such small airplanes are capable of performing useful surveillance missions in peace time and during conflicts. As these airplanes operate at very low flight speeds in the range of about 10–20 m/s, their performance is strongly affected by the low Reynolds numbers characteristic of such flight. In this article, we consider the special aerodynamic and propulsion problems associated with the flight of such small airplanes.

1. Introduction

Unmanned airplanes were considered over sixty years ago for missions that were either unsuitable or very risky for manned airplanes. The buzz-bombs employed by the Germans in World War-II were essentially unmanned airplanes with built-in bombs and replaced manned bombers. They are the forerunners of the current day cruise missiles.

Subsequently unmanned airplanes, generally called the drones, were developed for use during training as targets for antiaircraft guns or missiles. In parallel with these developments, small model airplanes have been developed for hobby and sport and are very popular. Occasionally such airplanes have also been built for research purposes. In these applications, the airplanes can be much smaller than manned airplanes and will be cheaper.

Currently, due to recent great advances in technologies of computers, communication devices, sensors and actuators and the resulting increase in performance and reduction in size and weight, unmanned airplanes under computer control can be much smaller. They are now capable of performing missions of far greater complexity than before. They are being used for new applications including surveillance and limited air combat. Mini airplanes of only a few kilograms in weight are being used for military and civil surveillance applications. There is much current interest in even smaller micro air vehicles of overall size of about 15 cm weighing around 100 gm. Even such vehicles appear to be capable of performing useful military missions either as single surveillance platforms or in groups of intercommunicating platforms carrying optical, chemical or other sensors. In what follows, we shall be concerned with the aerodynamic and flight mechanical aspects of such mini and micro air vehicles (MAVs).

2. Aerodynamics of Mini and Micro Airplanes

In principle, MAVs suitable for applications indicated above are not different from larger airplanes. However due to their very small size and weight, their performance parameters (speed, range and endurance) are not comparable to that of larger airplanes. As power required for flight increases with flight speed and the power that can be made available on board is limited by size and weight, the flight speed of MAVs is usually in the range of only 10–20 m/s. The vehicles fly at an altitude of a few hundred meters from their launching location (except when dropped from high flying airplanes) and are subjected to gusts and winds which are often active near ground level. The gusts and winds have a speed range comparable to the flight speed of the MAVs and thus stability and control aspects of MAVs pose some difficult problems. It appears that MAVs can only be useful under favorable atmospheric conditions.

Small size and low flight speed of an MAV results in a very low flight Reynolds number. This has a major influence on the choice of the airfoil for the vehicle.

Due to the small size and low flight speed of MAVs as indicated above, the flight Reynolds number R of these vehicles is generally in the range of 50,000 to 120,000. This range is far below the range of about 10^6 to 10^8 common in manned airplanes. As the aerodynamic performance of an airfoil (as indicated by the maximum lift coefficient or the maximum lift to drag ratio) is strongly dependent on the flight Reynolds number, an airfoil used on a large airplane is generally unsuitable for use on an MAV. As a consequence, a careful study of airfoil profiles suitable for low Reynolds numbers is required. An understanding of flow phenomenon at very low R is very helpful in such a study. These phenomena are briefly described below.

3. Flow at Low Reynolds Numbers

In order to understand the special problems associated with very low R, we consider the flow over a typical airfoil as the R varies in the range of 10^7 to 10^4. We begin with an airfoil placed in a stream at a small incidence and a high R of 10^7. Under these conditions, the boundary layers developing on the upper and lower surfaces of the airfoil are laminar for some distance along the surfaces and become turbulent and continue downstream all the way to the trailing edge. The boundary layers are attached all the way and there is little flow separation. The transition from laminar flow to turbulent flow at this R is so rapid that it may be assumed to take place at a point on the surface of the airfoil. This situation is illustrated in *Figure* 1. As we increase the incidence of

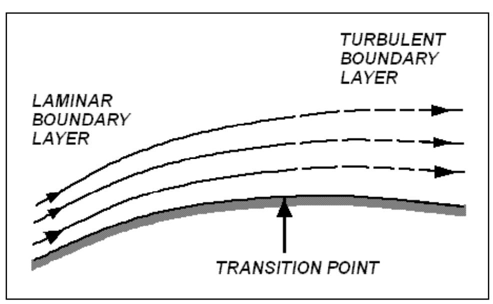

Figure 1. Transition at a Reynolds number of over 10^6. The boundary layer developing on the top surface of an airfoil is laminar near the leading edge. It becomes turbulent downstream at a location depending on the pressure distribution on the airfoil which is a function of airfoil profile and incidence. At high Reynolds numbers, this transition is so rapid that it may be considered instantaneous. After transition, the boundary layer remains attached and continues downstream.

the airfoil, the nature of flow is similar to the above, but the transition point moves somewhat upstream. There may also be some flow separation on the top surface as we approach the trailing edge. The drag of the airfoil in this condition is mainly due to skin friction in the boundary layers and is small. The ratio of lift to drag is high.

Next we consider the same flow but at a lower R somewhere in the range of 10^5 and 10^6. At very small incidence, the boundary layers on the airfoil surfaces are as indicated above with the difference that transition from laminar flow to turbulent flow takes place later (further downstream) and takes up a small distance along the airfoil. As the incidence is increased, the laminar boundary layer, being less capable of overcoming the pressure gradient on the top surface of the airfoil, separates. However the separated shear layer turns turbulent and reattaches itself and continues as a turbulent boundary layer further downstream. This is the phenomenon of transition through a laminar bubble and is illustrated in *Figure* 2. In this condition also the drag is mainly due to skin friction and is low.

Next we consider the same flow at a still lower R of about 5×10^4. At very small incidence, the boundary layers on the airfoil surfaces are wholly laminar. As the incidence is increased to a moderate value, the laminar boundary layer on the top surface separates. Unlike in the previous case, the laminar shear layer produced by separation remains laminar and does not reattach itself

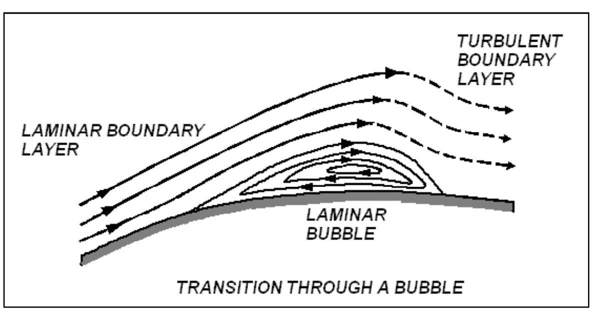

Figure 2. Transition at a Reynolds number in the range of about 10^5–10^6: At a Reynolds number in the range of about 10^5–10^6, the transition to turbulence occurs through a laminar bubble. The boundary layer first separates in a laminar condition to form a free shear layer. The free shear layer then becomes turbulent and reattaches itself as a turbulent boundary layer and continues downstream as attached flow. There is a closed region of separated flow close to the wall which is called the laminar bubble.

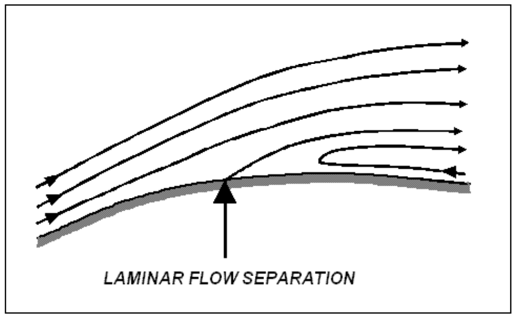

Figure 3. Flow at very low Reynolds numbers: Below a Reynolds number of about 50,000, the laminar boundary layer which separates from the airfoil surface remains separated as transition to turbulent flow is not possible in any reasonable distance along the flow direction. The airfoil performance is drastically affected.

to the air-foil surface. This leads to a large region of separated flow as illustrated in *Figure* 3. The airfoil drag is high due to low pressure in the separated region.

Thus it will be seen that as the R for the flow past an airfoil is decreased successively, we may expect a rise in its minimum drag to lift ratio as we approach 10^4. For a typical airfoil, this rise is so sudden that the R at which this happens is called the critical Reynolds number (R_{cr}) of the airfoil. R_{cr} of an airfoil depends on its profile. In particular, it depends on its thickness and leading edge radius. Thin airfoils and airfoils with sharp leading edges have a lower R_{cr}. Some modern thick airfoils have an R_{cr} as high as 10^6. It is obvious that such airfoils are unsuitable for micro air vehicles operating at R values around 10^5.

One may compare the above behavior of an airfoil with that of a cambered thin plate of about 2% thickness and 5% camber. As the R is decreased from around 10^5 towards 10^4, we do not pass through any critical value. The drag remains low throughout the range. Flow visualization at an R of 40,000 by Laitone [1] indicates that the large flow velocities induced near the thin leading edge lead to the formation and shedding of a sequence of vortices which roll down the surface of the airfoil and approximate an attached flow. A large wake is not formed. A thin flat plate exhibits a similar characteristic though its drag is higher than that of a cambered plate. These results are illustrated in *Figure* 4 constructed using data

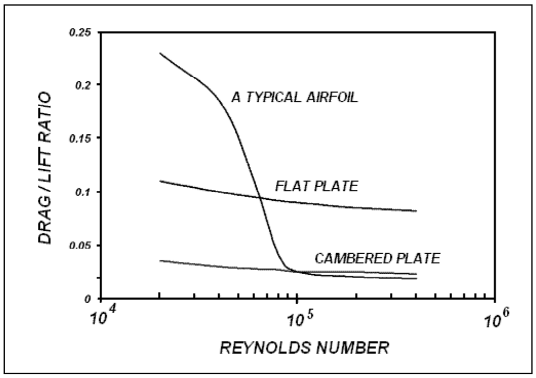

Figure 4. Critical Reynolds number of airfoils: The drag to lift ratio of a typical airfoil drops rapidly around a Reynolds number defined as its critical Reynolds number. This number depends on the profile of the airfoil but is typically around 50,000. Flat and curved plates with a small thickness ratio of 2% do not show this behavior.

from Jansen and Smulders [2]. This data is originally due to Schmitz [3] who is often quoted.

4. Choice of an Airfoil for a given Reynolds Number

It is clear from the above discussion that the choice of an airfoil for a specific application must give due attention to the range of R in that application.

As already stated, large airplanes operate at R values of over 10^7. In this case, the boundary layer transition on the airfoil surfaces is very rapid. As the laminar skin friction is lower than friction in a turbulent boundary layer, the drag of the airfoil can be reduced by keeping the boundary layers laminar as far as possible by suitably shaping the airfoil. Airfoils which achieve this are called the natural laminar flow (NLF) airfoils. These can be designed taking into account the flight Mach number as well. Modern airplanes make use of such airfoils extensively [4].

For lower R in the range of 10^5 to 10^6, advantage can be taken of transition through a laminar bubble to enhance airfoil performance. Airfoils have been designed by Wortman [5] and Selig [6] for sailplanes and unmanned airplanes using this concept.

These airfoils are called the low Reynolds number airfoils and have been successfully employed.

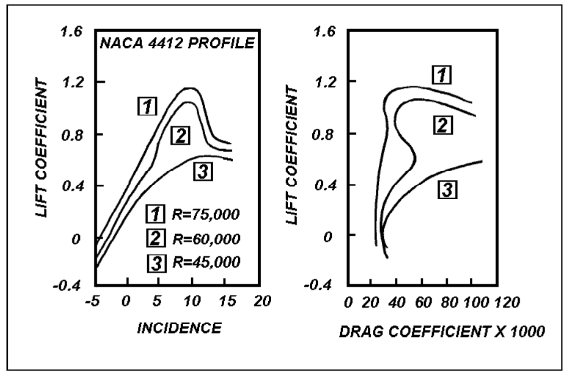

Figure 5. Airfoil behavior near its critical Reynolds number: At a Reynolds number of 75,000, the drag coefficient remains low till the approach of stall at a C_L of about 1.1. At a Reynolds number of 45,000, the airfoil stalls at a C_L of about 0.6 due to laminar separation. At a Reynolds number of 60,000, as the incidence is increased, the airfoil begins to stall due to laminar separation at a C_L of about 0.6 but recovers at a higher incidence due to turbulent reattachment to finally stall at a C_L of about 1.0.

For very low R below 50,000, conventional airfoils are generally unsuitable. This is illustrated in *Figure* 5 which shows the aerodynamic characteristics of NACA 4412 airfoil in the Reynolds number range of 45,000 to 75,000. It will be seen that at an R of 75,000, the airfoil has a maximum lift coefficient of about 1.1 characteristic of the turbulent boundary layer at separation on the upper surface of the airfoil. At an R of 45,000, the maximum lift coefficient is only about 0.6 which is typical of laminar boundary layer separation on the upper surface of the airfoil. At an R of 60,000 the airfoil shows some unusual behavior. As the incidence of the airfoil is increased, the drag coefficient rises up to a lift coefficient of about 0.6 showing the effect of laminar flow separation. However, with further increase of incidence, the drag coefficient drops sharply due to the reattachment of the boundary layer through a laminar bubble.

The airfoil thus shows a maximum lift coefficient around 1.0 corresponding to turbulent boundary layer separation at stall. It is quite obvious that an airplane using this profile will exhibit erratic behavior at an R around 60,000.

In the light of the above, thin curved plates and thin airfoils with sharp leading edges appear to be well suited for R less than 50,000. But these have not been studied extensively in the literature. However, insects with a flight flight R in the range of 1000–10,000 have wings approximating flat or curved plates indicating that these simple shapes may be the most suitable for this range.

5. Propulsion of MAVs

At the flight speeds typical of MAVs of around 10–20 m/s, propellers form the most convenient means of generating the thrust required. However, flapping wings offer a practical alternative. We consider these in some detail below.

In principle, small propellers are no different from the large airplane propellers. However, the blades of the tiny propellers operate at a flow R comparable to that of wings of MAVs and airfoil profiles have to be carefully chosen. In general, thin profiles with sharp leading edges appear well suited.

At the low end of the MAV range, it is practical to generate the propulsive force for the airplane using wing flapping. Birds and insects have been using this mode of propulsion for ages [7]. We explain below the general principles involved in bird flight.

A typical wing of a bird in level flight performs a flapping motion. The motion is roughly a periodic rotation of the wing about its root. A typical cross-section of the wing some distance away from the root thus moves up and down. However, the movement is not strictly one dimensional. The movement has a fore-aft component and a rotation (pitch) about a span-wise axis. During a complete cycle of flapping motion, the fore-aft motion and pitch angle vary in a complex manner. The downward motion of the wing is largely responsible for thrust generation. The upward motion is required for returning the wing to the starting position and has to be performed without creating excessive drag or losing lift. The mechanism of generation of lift and thrust can be explained using quasi-static aerodynamic considerations as folows.

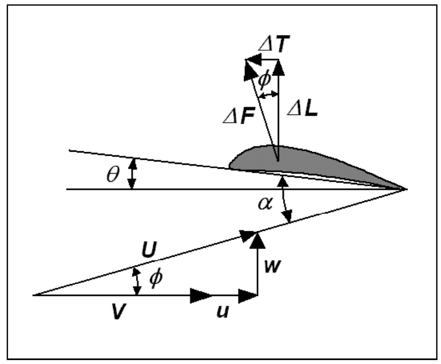

Figure 6. Forces on an airfoil due to flapping motion: Due to flapping motion, the velocity vector relative to a typical wing section some distance along the span of the wing is affected. The aerodynamic force on the section which is nearly perpendicular to the relative velocity vector has a component along the flight direction (thrust). The sum total of thrust due to all the sections of the wing constitutes the propelling force for the bird.

Figure 6 Illustrates an airfoil representing the cross-section of a bird's wing at a station some distance from the wing root. Due to the flight of the bird, there is a relative wind of magnitude V in the horizontal direction. Due to the flapping motion of the wing, the cross-section has a downward velocity component w and a small forward velocity component u. The wing section makes an angle θ with the horizontal. The variables u, w and θ can be positive or negative and vary continuously during a cycle of flapping motion. At any instant, the force components along and perpendicular to the flight direction due to unit depth of the airfoil, ΔT and ΔL, can be calculated by resolving the total aerodynamic force ΔF on the airfoil. For simplicity, we neglect the drag of the airfoil and obtain the following relations:

$$U^2 = (V^2 + u^2) \tag{1}$$

$$\tan\phi = \frac{w}{V+u} \tag{2}$$

$$\alpha = \theta + \phi \tag{3}$$

$$\Delta F = \frac{\rho U^2 C C_L(\alpha)}{2} \tag{4}$$

$$\Delta T = \Delta F \sin\,\phi = \frac{\rho U w C C_L(\alpha)}{2} \tag{5}$$

$$\Delta L = \Delta F \cos\,\phi \tag{6}$$

From the above equations we note the following. The thrust generated depends on the product of the horizontal velocity component and the vertical component as in (5). It is clear that sections farther from the root which have a larger vertical motion contribute more to the thrust. Next, we note that when the flight speed V, and hence U, is large as in cruise, a small w is adequate to generate sufficient thrust ΔT. When V is small as during take-off, a larger w implying a larger flapping motion is required. This is consistent with general observations of large birds which struggle during take-off by flapping rapidly.

Complex motion involving a combination of fore-aft, up-down and rotatory motion about the pitch axis is required for efficiently producing the required lift and thrust using the same wing, particularly at zero or small flight speeds.

When V is small or zero as in hover, the aerodynamic lift ΔL can be increased by increasing u which is related to the fore-aft motion of the wing. This is consistent with the observation of humming birds which move their wings rapidly fore-aft during hovering.

It will be seen from (3) that the wing incidence α directly depends on the wing pitch angle θ. To prevent stall which results in a loss of lift ΔL, the pitch angle has to be continuously adjusted during the flapping cycle. Birds and insects achieve this effectively. High speed photographs of humming birds and insects indicate rapid rotations of their wings in pitch during hovering. It appears that the local incidence of an insect wing during a cycle is limited to a value below about 30 degrees. It appears that the inherent flexibility of bird and insect wings are helpful in this task.

The above observations are only indicative of the complexities of flight of birds and insects. Unsteady aerodynamic effects not considered above are known to play an important role especially in insect flight. In particular, vortex shedding associated with the unsteady motion of a wing and interactions of the wing with its own shed vortices are important.

Returning to the subject of propulsion of MAVs using flapping wings, we may observe the following. If the MAV is only for cruise flight, simple up-down flapping motion of the wings may be adequate. But the flexibility of the wing has a significant influence on performance and has to be carefully designed in. Bird-like MAVs using this concept have been designed and flown successfully. However, much study is required before an insect-like MAV with a hovering capability can be realized.

Suggested Reading

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