Text Lecture 5a - Airfoils

In the first module airfoils were briefly discussed, and in previous lectures of the present module we already talked about airfoils in a more general way when we discussed pressure distributions, transition, separation and the effect of the Reynolds number. Now we will zoom in on the airfoil characteristics.

First of all, when we talk about airfoils we assume this is the cross section of an infinitely long, constant chord wing. This is what we call a "two-dimensional" situation. The general equation for the lift force on a wing is L=1/2 rho V-squared times the lift coefficient CL times the wing area S. The same goes for the drag force and the drag coefficient CD. However, since in the two-dimensional case the wing area is undefined, because the span is infinite, we talk about the force per meter span. So, S in the 2-dimensional case is c times 1. Note that – to show the difference- for the airfoil we use the small l and d and for the wing the capital L and D as subscript. Note the c squared in the moment coefficient equation, coming from the lever arm.

Here are a few definitions: The angle between the airfoil chord line and the incoming free stream vector is called the angle of attack. By definition the lift force is perpendicular to the incoming flow vector and the drag is parallel to it. The moment is positive nose-up, so when it tries to increase the angle of attack.

The moment is given with respect to the quarter-chord point. This is close to the aerodynamic center, where the moment doesn't change with varying angle of attack.

The performance of an airfoil is presented in lift, drag and moment characteristics. Here you see an example of the measured lift and drag characteristics as a function of the angle of attack for airfoil NACA 64 2 415.

Let's take a closer look at the lift curve.

In the range of small angles of attack the boundary layer remains attached to the surface and the lift coefficient changes linearly with the angle of attack. The slope of the lift curve is called the lift-gradient. When for the first time there is some separation at the trailing edge the lift curve starts to deviate from a straight line. With increasing separation also the lift curve levels off, until the maximum lift coefficient is reached. At this point the boundary layer separation roughly lies at 85 to 90 % of the chord. If we would further increase the angle of attack, separation moves forward until the boundary layer separates right from the leading edge. This situation is called "deep stall", characterized by a dramatic increase in drag and a decrease in lift.

As you can see in the plot of the drag coefficient the drag goes up quite rapidly when the angle of attack exceeds a certain value, both for positive and negative angles. This is due to the fact that the transition location moves forward in the direction of the leading edge, which means that a larger part of the airfoil has a turbulent boundary layer. When separation starts at the trailing edge also the pressure drag contributes significantly to the total drag. Because of its shape the drag curve sometimes is called "the drag bucket".

Generally, the characteristics are presented in a different way, like is shown here. The lift curve is the same (although we added an additional axis for the moment coefficient), but now the lift is presented as a function of the drag. In this way we can easily see at what lift coefficient the airfoil has its best performance: the maximum lift-drag ratio. It is the tangent to the drag-lift curve. The lift coefficient is called "the design lift coefficient". Note that the moment coefficient is negative, which means that the airfoil has a nose-down moment at every angle, keeping the airfoil stable.

Since the early days of flight there has been a constant quest for the right airfoil. First it was trial and error, but with the aid of wind tunnels later on the research became more coherent. This picture is quite popular since it shows a number of developments in the beginning of the 20th century. The Gottingen research has already be mentioned when we talked about Prandtl and his work.

An important boost to the understanding of the aerodynamics of airfoils and wings was given by the foundation in 1915 of the NACA, the National Advisory Committee for Aeronautics in the USA. The NACA performed a systematic theoretical and experimental investigation on the effect of maximum thickness, thickness distribution, camber, camber distribution, Reynolds number, Leading edge roughness, high lift devices, etc. etc. on the performance of airfoils for aeronautical application. In the 19 thirties the NACA 4 digit and 5 digit airfoils series were developed, such as NACA 4415 and NACA 23015. Also the NACA 0012, a 12% thick symmetrical airfoil saw the light. It was later on mostly used for helicopters and it is probably the most tested airfoil in the world. The airfoils were generated combining different mean camber lines with various symmetric thickness distribution, as is shown on this slide.

In the 19 40s the NACA 6digit airfoil families were made, such as the NACA 63, 64 and 65 airfoil series. Although systematic in the use of the mean lines, they were already designed from a desired inviscid pressure distribution point of view.

These are laminar airfoils. It was found that when the surface of the wings could be maintained sufficiently smooth (which was not so easy in the early days) a significant amount of laminar flow could be realized with these airfoils. The older ones are called turbulent airfoils, since at moderate angles of attack they have the transition location closer to the leading edge. The NACA measurements give us the possibility to compare the performance of these airfoils. The difference in shape between a 4 digit and a 6 digit airfoil is shown here. Both are 18% thick. The 4 digit airfoil has a thicker upper surface.

The upper part of the lift curve is the same for both airfoils, but the 63-series airfoil has a lower drag and also a better lift-drag ratio. This slide here shows the lift as a function of the lift-drag ratio. If we compare the maximum lift-drag ratios of both airfoils, we can see that the difference is 10%. If we would compare an 18% thick member of the 64-series, which has more laminar flow over the upper surface than the 63 series airfoil shown here, the difference would even be larger.

The next slides show the impact of the camberline on the performance of a 63-series airfoil with a thickness of 18%. For clarity, the index in the airfoil name after the 3 has been omitted. With increasing camber starting from a symmetric airfoil (denoted by the 0, 2, 4 and 6 in the airfoil names) the lift curve shifts upward. The lift gradient remains approximately constant.

The NACA experiments not only have given great insight in the impact of airfoil shape on the performance, a number of these airfoils are still being used today, more than 70 years later.

Later developments were done at the National Aeronautical and Space Administration NASA the successor of NACA, founded in 1958.

In the post war time the emphasis was put more on high subsonic and transonic flight, which resulted in the generation of super-critical airfoils designed by Richard Whitcomb in the nineteen sixties

What already had started with the development of the 6 digit series, now the airfoils were derived by shaping the pressure distributions in such a way that the required performance was achieved. Examples for low-speeds and light aircraft are the low-speed (LS) series of airfoils from the 1970's and the Natural Laminar Flow airfoils from the eighties. Two of these airfoils are shown here. The NLF airfoil is 16% thick. The LS airfoil 17%.

The big aircraft companies like Boeing and Airbus have always used in-house developed airfoils for their aircraft wings of which the shapes for obvious reasons seldom see the public domain.

Next time about calculating the lift from the pressure distribution and how to incorporate the impact of the Mach number on the lift-curve.