SUBSONIC AIRFOIL DESIGN

HISTORICAL BACKGROUND

From its very beginning, the National Advisory Committee for Aeronautics (NACA) recognized the importance of airfoils as a cornerstone of aeronautical research and development. In its first Annual Report to the Congress of the United States, the NACA called for "the evolution of more efficient wing sections of practical form, embodying suitable dimensions for an economical structure, with moderate travel of the center of pressure and still affording a large range of angle of attack combined with efficient action" (ref. 1). By 1920, the Committee had published a compendium of experimental results from various sources (ref. 2). Shortly thereafter, the development of airfoils by the NACA was initiated at the Langley Memorial Aeronautical Laboratory (ref. 3). The first series of airfoils, designated "M sections" for Max M. Munk, was tested in the Langley Variable-Density Tunnel (ref. 4). This series was significant because it represented a systematic approach to airfoil development as opposed to earlier, random, cut-and-try approaches. This empirical approach, which involved modifying the geometry of an existing airfoil, culminated in the development of the four- and five-digit-series airfoils in the mid 1930's (refs. 5–7).

Concurrently, Eastman N. Jacobs began work on laminar-flow airfoils. Inspired by discussions with B. Melvill Jones and G. I. Taylor in England, Jacobs inverted the airfoil analysis method of Theodore Theodorsen (ref. 8) to determine the airfoil shape that would produce the pressure distribution he desired (decreasing pressure with distance from the leading edge over the forward portion of the airfoil). This pressure distribution, it was felt, would sustain laminar flow.

Thus, the basic idea behind modern airfoil design was conceived: the desired boundary-layer characteristics result from the pressure distribution which results from the airfoil shape. The inverse method mathematically transforms the pressure distribution into an airfoil shape whereas the designer intuitively/empirically transforms the boundary-layer characteristics into the pressure distribution.

The resulting 2- through 7-series airfoils, the most notable of which are the 6-series, were tested in the Langley Low-Turbulence Tunnel and the Langley Low-Turbulence Pressure Tunnel (LTPT) in the late 1930's and early 1940's (refs. 9 and 10). To concentrate on high-speed aerodynamics, the NACA got out of the airfoil business in the 1950's, leaving the world with a large number of systematically designed and experimentally tested airfoils (ref. 11). The four- and five-digit-series, turbulent-flow airfoils produced relatively high maximum lift coefficients although their drag coefficients were not particularly low whereas the 6-series, laminar-flow airfoils offered the possibility of low drag coefficients although their maximum lift coefficients were not especially high. The quandary faced by the aircraft designers of the day over the type of airfoil to select, laminar- or turbulent-flow, was solved by the available construction techniques, which produced surfaces that were insufficiently smooth and rigid to support extensive laminar flow.

The airfoil scene then shifted to Germany where F. X. Wortmann and Richard Eppler were engaged in laminar-flow airfoil design. Wortmann employed singularity and integral boundary-layer methods (refs. 12–14) to develop a catalog of airfoils intended primarily for sailplanes (ref. 15). Because the theoretical methods he used were relatively crude, however, final evaluation of the airfoils was performed in a low-turbulence wind tunnel. Eppler, on the other hand, pursued the development of more accurate theoretical methods (refs. 16 and 17.)

The successor to the NACA, the National Aeronautics and Space Administration (NASA), reentered the airfoil field in the 1960’s with the design of the supercritical airfoils by Richard T. Whitcomb (ref. 18). The lessons learned during the development of these transonic airfoils were transferred to the design of a series of turbulent-flow airfoils for low-speed aircraft. The basic objective of this series of airfoils was to achieve higher maximum lift coefficients than the earlier NACA airfoils. It was assumed that the flow over these airfoils would be turbulent because of the construction techniques then in use by general aviation manufacturers. While these NASA, turbulent-flow airfoils (ref. 19) did achieve higher maximum lift coefficients, the cruise drag coefficients were no lower than those of the NACA four- and five-digit-series airfoils. Emphasis was therefore shifted toward natural-laminar-flow (NLF) airfoils in an attempt to combine the low-drag characteristics of the NACA 6-series airfoils with the high-lift characteristics of the NASA low-speed airfoils. In this context, the term ‘natural-laminar-flow airfoil’ refers to an airfoil that can achieve significant extents of laminar flow (≥ 30-percent chord) on both the upper and lower surfaces simultaneously, solely through favorable pressure gradients (no boundary-layer suction or cooling).

The advent of composite structures (ref. 20) has also fueled the resurgence in NLF research. This construction technique allows NLF airfoils to achieve, in practice, the low-drag characteristics measured in low-turbulence wind tunnels (ref. 21).

Today, airfoils are being designed for an ever-widening range of applications (ref. 22). Examples include unmanned aerial vehicles (ref. 23), cooling-tower fans (ref. 24), sailplanes (refs. 25 and 26), wind turbines (refs. 27 and 28), rotorcraft (ref. 29), and general aviation (ref. 30), commuter (ref. 31), and transport aircraft (ref. 32).

PHILOSOPHY

At this point, it is important to emphasize that the goal of the effort at NASA Langley Research Center was *not* the design of a series of natural-laminar-flow airfoils for low-speed aircraft. Rather the philosophy of Richard Eppler was adopted, which is to develop a (theoretical) method and verify it such that others can use the method to design airfoils for their own specific applications. The key to the success of this philosophy is the verification of the method. The objective then was to accomplish this verification through selective testing of various airfoil concepts in the Langley Low-Turbulence Pressure Tunnel.

Note that this philosophy is contrary to the approach taken by the NACA and F. X. Wortmann. They developed catalogs from which aircraft designers could select airfoils for their proposed vehicles. This approach was necessary for the NACA because the theoretical methods of the day were too primitive to predict accurately the aerodynamic characteristics of an airfoil. The use of catalogs has been successful, however, because the applications for which the airfoils were used were indeed those for which the airfoils were intended. In addition, the section characteristics were painstakingly measured in good, low-turbulence wind tunnels at the appropriate Reynolds numbers. Thus, the airfoils, their measured characteristics, and their applications coincided well. As applications have become more diverse, however, the older airfoils and the measured characteristics have become less appropriate. Today, with applications ranging from fans to transport aircraft, the use of airfoils designed for aircraft having Reynolds numbers of 3 to 9×10^6, low Mach numbers, and relatively low lift coefficients is unacceptable. For some applications, the use of such airfoils is particularly unsuitable because the design requirements for these low-speed aircraft airfoils are significantly different from those for the airfoils for the other applications; wind turbines are a good example (ref. 33).

The catalogs also suffer from a lack of coverage. Each application requires a specific performance from the airfoil. If this performance falls within the range of characteristics contained in a catalog, an airfoil can be selected from that catalog for the given application. More than likely, however, this airfoil will still represent a compromise because its characteristics do not match exactly those of the application.

A related advantage of the theoretical airfoil design method is that it allows many different concepts to be explored economically. Such efforts are generally impractical in wind tunnels because of time and money constraints.

Thus, the need for a theoretical airfoil design method is threefold: first, for the design of airfoils that fall outside the range of applicability of existing catalogs; second, for the design of airfoils that more exactly match the requirements of the intended application; and third, for the economic exploration of many airfoil concepts.

The ultimate acceptance of this philosophy faces one final hurdle that can be summed up by the following saying:

> No one believes the theory except the one who developed it.
> Everyone believes the experiment except the one who ran it.

This hurdle can be overcome by a rigorous verification of the method.

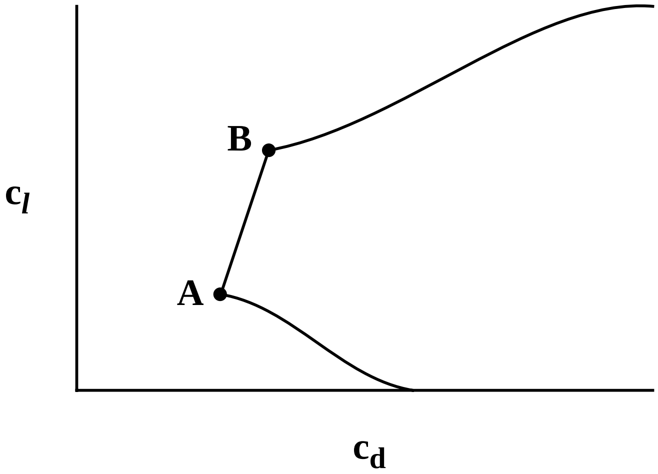
THEORY

In 1975, NASA personnel began working with the Eppler Airfoil Design and Analysis Code (refs. 22 and 34). This code contains a conformal-mapping method for the design of airfoils with prescribed velocity-distribution characteristics, a panel method for the analysis of the potential flow about given airfoils, and a boundary-layer method. With this code, airfoils with prescribed boundary-layer characteristics can be designed and airfoils with prescribed shapes can be analyzed.

In all other inverse methods, the velocity (pressure) distribution is specified at one angle of attack and the airfoil shape that will produce that velocity (pressure) distribution is computed. Thus, the airfoil is designed at a single point. All other conditions are considered “off-design” and must be taken into account intuitively and analyzed later to determine acceptability.

The conformal-mapping method in the Eppler code is unique because it allows the velocity distribution to be specified along different segments of the airfoil *at different angles of attack.* This is an extremely powerful capability because it allows the important features of many velocity distributions to be incorporated into the airfoil design from the outset. Thus, the airfoil is designed at several points simultaneously and the off-design conditions can be taken into account in the initial specification.

The following sketch helps to illustrate, in a very simplified way, the use of this capability.



As determined from the desired application performance, the airfoil must produce low drag over the range of lift coefficients from points A to B. Point A corresponds to the lift coefficient below which the transition point moves rapidly forward along the lower surface. Thus, for this point, the design of the lower surface is critical. Point B corresponds to the lift coefficient above which the transition point moves rapidly forward along the upper surface. For this point, the upper surface is critical. Using conventional design methods, the velocity distribution must be specified at point A or point B or, possibly, some intermediate point. With the Eppler code, however, the velocity distribution along the lower surface at point A is specified as is the distribution along the upper surface at point B.

It should be noted that the actual, absolute velocity distributions are not specified in the method, only the velocity gradients. For details, see reference 34.

The panel method allows the velocity distribution about a given airfoil to be computed. This is obviously required for the analysis of specified airfoil shapes but, with respect to airfoil design, it is also necessary for determining the effect of a simple flap deflection on the velocity distribution. This method employs third-order panels with vorticity distributed parabolically along each panel.

An integral method is used for the prediction of the boundary-layer development for each velocity distribution. The method can predict laminar and turbulent boundary layers, transition, and separation, both laminar and turbulent. The drag due to laminar separation bubbles is also predicted. The method is semi-empirical and contains a boundary-layer displacement iteration.

An important feature of the Eppler code is the connection between the boundary-layer method and the conformal-mapping method. This connection allows the boundary-layer characteristics to be controlled directly during the airfoil design process. This is a particularly significant capability for the design of laminar-flow airfoils and represents a major step forward from the procedure used to design the NACA laminar-flow airfoils. Now, instead of intuitively or empirically transforming the desired boundary-layer characteristics into a velocity distribution, the designer can determine directly the modifications to the velocity distribution that will produce the desired boundary-layer development at any given angle of attack.

VERIFICATION

To verify the theory, several airfoils have been designed using the Eppler code and the majority have been tested in low-turbulence wind tunnels, including the Langley Low-Turbulence Pressure Tunnel (refs. 35 and 36), the low-turbulence wind tunnel of the Delft University of Technology Low Speed Laboratory (ref. 37), and The Pennsylvania State University low-speed, low-turbulence wind tunnel (ref. 38). See references 39–41, for example.

CONCLUDING REMARKS

Airfoil design has progressed considerably over the past century. The first airfoils were mere copies of birds's wings. These airfoils were followed by cut-and-try shapes, some of which were tested in simple, low-Reynolds-number wind tunnels. The NACA systematized this approach by perturbing successful airfoil geometries to generate series of related airfoils. These airfoils were carefully tested in a more sophisticated wind tunnel that could replicate flight Reynolds numbers. Eastman Jacobs recognized the need for a theoretical method that would determine the airfoil shape that would produce a specified pressure distribution that would exhibit the desired boundary-layer characteristics. This idea represents the basis of modern airfoil design: the desired boundary-layer characteristics result from the pressure distribution, which results from the airfoil shape.

The inversion of an airfoil analysis method provided the means of transforming the pressure distribution into an airfoil shape. The transformation of the desired boundary-layer characteristics into a pressure distribution was left to the imagination of the airfoil designer. Since that time, over 60 years ago, Richard Eppler, through his computer code, has developed a much more direct connection between the boundary-layer development and the pressure distribution.

NASA adopted the philosophy of Eppler that a reliable theoretical airfoil design method should be developed instead of catalogs of experimental section characteristics. The method can then be used to explore many concepts with respect to each specific application. The success of this philosophy hinges on the verification of the method.

Several airfoils have been designed to test Eppler's method. By investigating the airfoils in low-turbulence wind tunnels, the range of applicability of the method has been established. Initially, the classical, low-speed Reynolds-number range of 3 to 9×10^6 was investigated. From there, higher Reynolds numbers ($\sim 20 \times 10^6$) and Mach numbers (~0.7) were explored. More recently, lower Reynolds numbers ($\sim 0.5 \times 10^6$) have been investigated. The latest indications are that the method is also applicable at even lower Reynolds numbers ($\sim 0.1 \times 10^6$). The method has been steadily improved in response to inadequacies revealed during these experimental investigations.

In summary, an experimentally-verified, theoretical method has been developed that allows airfoils to be designed for almost all subcritical applications.

Further improvements in the science of airfoil design await more accurate theoretical methods. These improvements require fundamental experiments aimed at improving the prediction of the boundary-layer phenomena of transition and separation. These improvements are, however, not likely to lead to large increases in airfoil performance. Major improvements in airfoil characteristics await advances in the art of airfoil design, which is still the domain of the designer's creativity.

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