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AIRFOILS

Significance and Early Development

by

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Birds offered obvious prototypes for the design of wings used in early attempts to fly; even to the extent that many early designs were ornithopters. The wing shapes varied; some apparently being inspired less by birds than by medieval concepts of angels, devils, and legendary flying animals. Only gradually did the long graceful wings of the soaring birds become the dominant type. By the time of the Wright brothers it was known by the better informed enthusiasts that efficient wings must be long and slender. This, in turn, imposed a structural problem which, under the conditions of the time, was best solved by the biplane which permitted a deep, efficient truss. In as much as this was a passing solution lasting only a quarter of a century, the biplane will not be considered further.

The reason why efficient wings had to be long and slender was not understood although there was a vague concept that it was best to use as much air as possible to support the weight, and that this was achieved by long spans. This situation was claified to some extent by Lanchester in England and put on a firm footing by Prandtl in a paper first published in Germany in 1912, but the substance of which was not generally available in this country until after World War I.

Prandtl's paper proposed the lifting-line theory of wing aerodynamics in which the wing is replaced by a straight lifting line extending along the span and moving pependicularly through an infinite volume of perfect fluid having no compressibility or viscosity. Any section of the wing parallel to the direction of motion is considered to act independently of the others except for an induced angle of attack. The flow over any section is therefore two dimensional with no component along the span.

The solution of this problem is complex except for the single but typical case of elliptical span loading corresponding to an untwisted wing of elliptical plan form. this solution showed that there is an irreducible drag associated with lift and that this induced drag coefficient varies directly with the square of the lift coefficient and inversly as the square of the span.

A wing of infinite span would have no induced drag and the same flow pattern in all planes perpendicular to the span. In other words, the flow would be two dimensional thus satisfying this assumption of the lifting-line theory. The aerodynamic characteristics of wings of infinite span are accordingly called "wing section characteristics", or "airfoil section characteristics", or simply "airfoil characteristics". These characteristics are intrinsically associated with the shape of the wing section as contrasted with wing characteristics which are affected by wing planform and twist. Thus the concept of airfoil characteristics simplifies the study of wing characteristics by permitting them to be separated into two parts which may be considered separately.

If the characteristics of the airfoils are known, it is possible to calculate some characteristics of wings of arbitrary planform and twist such as the angle of zero lift, lift curve slope, span loading, and drag for the high speed and cruise conditions. It is also possible to obtain some general approximations to the wing maximum lift coefficient and stalling characteristics, although these approximations should be treated with extreme caution. Considering the nature of the many assumptions of the theory, it is a wonder that it is valid at all. Actually it works very well at low and moderate lift coefficients if no spanwise discontinuities or rapid changes of section, chord, or twist are present, if the wing has no pronounced sweep, and if the wing is of sufficient aspect ratio.

Unfortunately generalized solutions of the theory were too complex for direct mathematical attack before electronic computers became available. Accordingly much effort was spent by many prominent aerodynamicists to provide good approximate solutions. These solutions typically took the form of converging algebraic or trigonometric series which still required extensive computation. Unfortunately some people became so intrigued by the mathematics that they failed to distinguish between improvements to the theory and these attempts to simplify computation. This confusion resulted in attempts to use the theory for purposes for which it was obviously unsuited with unfortunate results.

Even before the time of Prandtl it was appreciated that the shape of the wing sections was important, and flat sections quickly gave way to curved sections that were concave downward. Original curves were essentially circular arcs, but by 1909 Bleriot had progressed to increasing the curvature over the forward part of the section. By 1912 the sections were being made thicker to accomodate the spars, and the desirability of a rounded leading edge and of a sharp trailing edge was known. Tests were being made in wind tunnels of large numbers of wings with their shapes gradually improving as the result of experience. The Eiffel and early RAF series were outstanding examples of this approach.

The gradual development of both the Prandtl wing theory and of wing section theories such as those initiated by Joukowski from 1906 to 1910 and by Munk during World War I led to a more systematic approach. Joukowski had shown that a circle could be transformed into airfoils by a mathematical trick known as conformal transformation. The chief advantage was that the pressure distributions about the resulting airfoils could be computed but the process was laborious. Such airfoils and modifications of them were extensively tested at Gottingen during World War I. The development of thin airfoil theory by Munk implied that such characteristics as the angle of zero lift and the moment coefficient were determined primarily by the shape of the mean line - or camber - of the airfoil. This theory resulted in further extension of the work at Gottingen to include investigation of varying separately the camber, the thickness, and the thickness distribution. This work contributed greatly to the development of modern airfoils. Despite the common use for a while of such airfoils as the RAF 6 and 15, the Curtiss C-27 and C-62, the USA 27 and 35-B, and the famous Clark Y, most airfoils in common use up to World War II were derived from more or less direct extension of the work at Gottingen.

By the middle twenties the scene of the most important airfoil research shifted from Gottingen to the Langley Laboratory of the National Advisory Committee for Aeronautics in Virginia. This was the direct result of the employment at the laboratory of Munk, and the wisdom of the Committee in accepting his advice to build the Variable Density Wind Tunnel. This was an unprecedented venture in magnitude of expenditure and in technological advance. All previous wind tunnel research on airfoils had been severly handicapped by the small scale of the tests - measured by Reynold's number. Experience had shown that the results of tests of small models could not be applied directly to full scale flight conditions, and neither theory nor experience provided any means for correcting the results. Small scale models were, however, essential to research, both because the small wind tunnels then existing would not accomodate large models, and because big models for the large wind tunnels later to be built were too expensive and cumbersome for extensive research. The Variable Density Wind Tunnel (VDT) avoided this problem by obtaining essentially full scale results from tests of small models, usually 5 by 30 inches, at 20 atmospheres pressure.

Munk's work at Langley extended the work at Gottingen by producing the M-series airfoils for which the effects of camber, thickness, and thickness distribution were investigated. These airfoils never became popular, however, partly because of the short time before the departure of Munk from Langley and the destruction of the tunnel by fire in 1927, and partly because the research was not well directed to the production of airfoils suited to the needs of the time.

When I arrived for work at Langley in June 1929, I found that the VDT had been redesigned and rebuilt in steel, and the new balance had just arrived for installation. Jacobs, who had recently been put in charge of the tunnel, was starting work on what was to become the NACA four-digit series airfoils. It was already determined that the research would concentrate on the effects of thickness and camber, and it remained to select an initial thickness distribution and shape of camber.

Pinkerton found that the thickness distributions of efficient airfoils such as the Gottingen 398 and the Clark Y were nearly the same when the camber was removed and they were reduced to the same thickness. Jacobs accordingly selected a mathematically defined thickness distribution which corresponded closely to that for such airfoils. The mean lines to be used were selected as those defined by two parabolic arcs tangent at the position of maximum mean line ordinate. These cambers appeared suitable for positions of the maximum ordinate varying between 20 and 70 per cent of the chord. These variables having been selected, the first models having been made, and the balance having been installed, the research was ready to start.

Then the trouble began. The flow in the tunnel was attrocious and all attempts to fix it failed. Frequent electrical fires interrupted all work. The only solution was to tear the tunnel apart, redesign and rebuild. High authorities in the NACA were horrified and exasperated - justifiably so. No appropriations had been made to cover the cost of such work, and the recent crash on Wall Street assured that none would be obtainable. If we were going to have a tunnel, the dozen of us in the VDT Section would have to redesign and rebuild it ourselves. We did. In late 1930 the tunnel was working fine, and the research could begin.

The result of this research is too well known to warrent a long narrative. The NACA four-digit series airfoils were an almost instant success, and their use increased rapidly until it became nearly universal, both in this country and abroad. This success resulted partly because some of the airfoils were highly efficient, and partly because the systematic nature of the series provided designers with the data they needed to select the best thickness and camber for their particular needs.

The results indicated that the maximum lift capabilities of the airfoils increased as the position of maximum camber was shifted either forward or aft of approximately the mid-chord position. The rearward positions were not of much interest because of large pitching moments. The type of mean line used for the four-digit series was not suitable for extreme forward positions of the maximum camber, so a new series of mean lines was developed, and the resulting airfoils are the NACA five-digit series. The success of these airfoils emulated that of the previous series.

The success was so great that extension of the research to investigate such factors as changing the leading edge radius, the position of maximum thickness, the trailing edge angle, and reflexed mean lines was limited to testing the more promising combinations. Instead the available tunnel time was devoted to other wing problems such as wing-fuselage interference, including the development of fillets, high lift devices, and to the correlation of wing characteristics as predicted from the airfoil data with those actually existing for wings of various planforms and twists. This was not the case in Germany. As part of the greatly increased research activity after Hitler came to power and during the Second World War, German aerodynamicists investigated these NACA series airfoils more systematically than was done at Langley. The results of this work did not become generally available until after the war when they were no longer of much interest.

The work in the VDT, like other airfoil work, had, of course, been done by testing wings - in this case wings of aspect ratio 6. Airfoil characteristics were calculated from the test data by application of lifting line theory, and designers then reversed the process to calculate the characteristics of their wings. This was not very satisfactory. It was prudent for us to try whenever possible to correlate our airfoil results with wing characteristics measured in other facilities. Such correlations indicated that our results were being affected by turbulence of the air stream which exceeded that of most other wind tunnels. In an effort to correct for this effect, Jacobs devised a correction to what he called an "effective Reynold's number". This correction rested on an inadequate theoretical foundation and on slender correlations. The best that can be said about it is that it was probably better than nothing.

When the new NACA Full-Scale Wind Tunnel got around to making some wing tests, a real shock was experienced. These tests showed that the VDT results indicated a rate of increase of drag with thickness ratio much greater than the Full-Scale Tunnel. This discrepency was important because it directly affected the choice of wing thickness for the inner sections of monoplane wings.

As a result of this finding - and of some general suspicions - I undertook with the full backing of Jacobs a thorough investigation of all sources of consistent error in our results. The Full-Scale Tunnel results were shown to be the more nearly correct, and proper support interference corrections were provided for the VDT data. More importantly, this investigation led me to the conclusion that no changes in the VDT -or any other existing facility - would produce an adequate wind tunnel for airfoil research. Much to my surprise the NACA, in its honesty, published this conclusion.

The story about how this team headed by Jacobs conceived, designed and developed the NACA Two-Dimensional Low-Turbulence Wind Tunnels is too long to tell here. By the fall of 1941 - just before Pearl Harbor - the pressure tunnel was ready for operation. It provided a facility for the two-dimensional testing of airfoils at pressures up to 10 atmospheres in a test section 3 feet wide and 7½ feet high in an air stream of unprecedented uniformity and steadiness. War conditions dictated that this tunnel be used extensively for development testing, but, by operating it 24 hours a day 7 days a week, some time was found for airfoil research.

Meanwhile it had become apparent that continued empirical testing of airfoils, no matter how systematic, would not lead to greatly improved shapes except by luck. Lower drags could be obtained only by achieving more extensive laminar boundary layers, and higher critical speeds only by minimizing the induced velocities. These conditions required that the minimum pressure point be located unusually far back on both surfaces, and that there be a small but continuously favorable pressure gradient from the leading edge to the position of minimum pressure. Moreover, if the airfoils were to be practical, this situation must persist over a useful range of lift coefficients; the leading edge must be sufficiently large to permit reasonable maximum lift coefficients; and the pressure recovery over the rear of the airfoils must occur without excessive separation of the flow.

These requirements are conflicting, and their achievement, if possible at all, required a theory for designing airfoils to have desired pressure distributions. Successive attempts to design airfoils using approximate theoretical methods developed by Jacobs, Allen and others led to airfoils designated as the NACA 1- to 5- Series. These airfoils used mean lines that provided either a constant loading along the chord at the ideal lift coefficient, or a constant loading from the leading edge to some point from which the loading decreased linearly to zero at the trailing edge. These mean lines were derived from Munk's thin airfoil theory as extended by Glauert. Wind tunnel and flight tests of these airfoils provided much qualitative information about the characteristics to be desired, but failed to produce practical airfoils.

Experience with approximate theories showed that none of them was sufficiently accurate to show correctly the effects of changes in profile near the leading edge, and the search for a mathematically rigorous method continued. Theodorsen had derived a a method using conformal transformations for obtaining the pressure distributions of arbitrary airfoils as early as 1931, but the reverse process resisted all efforts. This theory could not be used successfully by the obvious method of successively changing the shape of the airfoils by small increments and calculating the resulting pressure distributions because this would have swamped the total computing capability of the laboratory with no assurance of success. None of us had any special training in mathematics, and no help could be obtained from Theodorsen or others who were approached. We were told that even the statement of the problem was mathematical nonsence with the implication that it was only our ignorance that encouraged us. Nevertheless, Jacobs was persistent - some said stubborn - and he devised a satisfactory method based on Theodorsen's work. Jacob's method consisted essentially of changing a function in the conformal transformation of Theodorsen's theory by small increments which resulted in changes in both the shape of the airfoil and of its pressure distribution, and also provided guidance for the successive step. This method as originally devised was used to design the early 6-series airfoils, and, as improved and refined by experience, to design the final series.

These airfoils like the previous 4- and 5-digit series were an immediate success. Before the war ended most American military aircraft were using them. Much disappointment was felt, however, because operational aircraft failed to achieve the very low drags measured in the wind tunnel because the surfaces could not be maintained sufficiently smooth and fair. Nevertheless, appreciable improvement was obtained, and, as airplane speeds increased, the high critical speeds of these airfoils proved to be their most valuable feature.

Then, as airplane speeds increased into the supercritical region with wing planforms changing to highly swept and low aspect ratio shapes, the importance of airfoils suffered a decline. When the maximum lift coefficient of an airfoil as measured on a wing could be either twice or half of that measured in two-dimensional flow, it was time to rethink the whole matter. The result was that airfoil research essentially stopped for some years as other problems received higher priority. It does not follow that airfoils are of no importance - far from it - but it does follow that modern wings for high performance aircraft must be considered as a whole. The simple methods of the past no longer yield satisfactory results.

As I look back on these simple methods, I am struck by the fact that so much of the effort - not only at the NACA - was devoted to surmount problems of computation. It must be very difficult for most of you to imagine conditions where all computation was done with pencil and paper or with slide rules as was the case up to the middle of the thirties, or with mechanical desk calculators which were greatly improved at that time. Valculation of the pressure distribution about an airfoil, or the design of an airfoil to have a special pressure distribution, which can be done today as fast as the problem can be typed into a computer, then required days or - sometimes - weeks. A similar situation existed with regard to applying wing theory to predict wing characteristics. These are the reasons we spent so much time devising methods whereby pressure distributions, wing loadings, etc. might be obtained for any wing using NACA airfoils in a few minutes by any designer whether knowledgeable about the theory or not, and using only paper, pencil and a 10-inch slide rule. All such methods have, of course, been superceded by the computer. I suspect that we have not heard the last of the computer, and that, as they continue to increase in capability, the methods of today will become obsolete at least as rapidly as the simple methods of the past.