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OSCILLATING AIRFOILS AND THEIR WAKE

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16. Abstract The unsteady phenomena in the wake of an oscillating wing or rotor blade are examined theoretically using the Prandtl approximation of the vortex-transport equation. A mathematical model is developed and applied to such problems as the effect of winglets on the performance of fixed wings and the possibility of employing similar designs in rotor blades. Model predictions for several profiles are compared with published experimental measurements, and good agreement is found. Graphs and diagrams are provided.

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OSCILLATING AIRFOILS AND THEIR WAKE

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Both aircraft with fixed wings and rotary aircraft fly according to the same principal of dynamic lift. The relative acceleration between air and airfoil necessary for lift can be attained by rotary aircraft while at a standstill. Even though ultimately different in their construction and lift principals, the two flight machines' airfoils are similar. /13*

To date, explanations of rotary blade cross sections depend upon two-dimensional profile theories of infinitely extended airfoils. In the same way, many dynamic investigations into rotary blades are carried out in even and homogenous oncoming flow, as it occurs for fixed wings. A number of simplified assumptions are necessary to adapt starting equations (maintenance statements for impulse, mass and energy), which are the basis of flow problems, to numerical evaluation. An approximation of circular rotary movement through a locally even oncoming flow is the most plausible approximation among these assumptions (Figure 1).

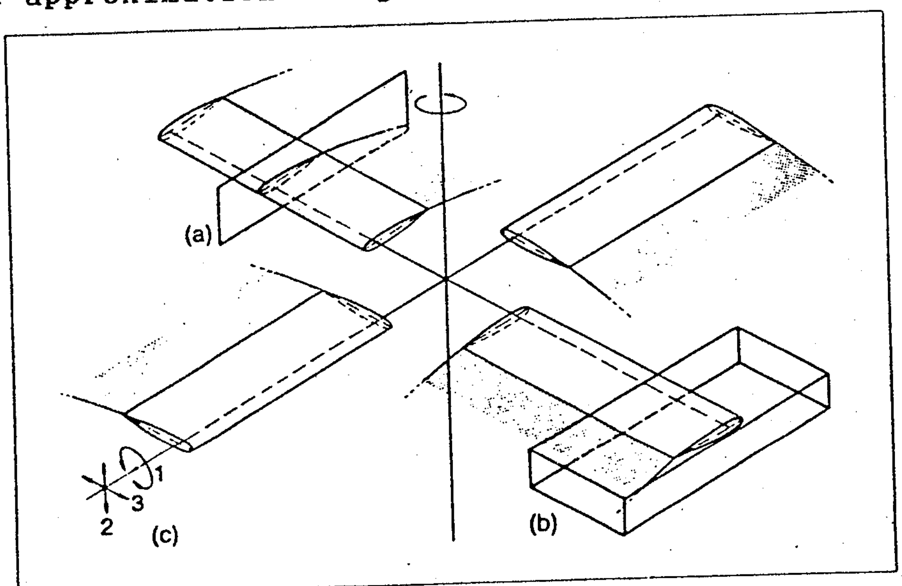


Figure 1: Airfoil of a rotor and approximations of profile theory (a), blade tips (b), unsteady flow theory (c), (1 = turning, 2 = driving, 3 = oscillating)

* Numbers in the margin indicate pagination in the foreign text.

** DFVLR Institute of Aeroelasticity, Goettingen, West Germany.

Pressure, which weighs upon a body in a flow of air, is the least interesting dimension among the typical specifications of aerodynamics. Powers and torques mechanically affecting construction come from this pressure. Resulting form and placement changes over the parameter conditions (of impermeability of the body's surface) lead to new acceleration fields and new pressure dispersion. In many cases this process takes place harmonically or at least periodically, so that simplified assumptions can be introduced even with regard to the timed progression of solutions to flow problems. Three aspects are of particular importance for airfoils. Each of these leads to different approximations:

1. pressure dispersion and its phase relation to movement form;
2. induced drag based on rotation of the wake;
3. friction drag of the airfoil.

With regard to unsteady processes, the third aspect is only loosely connected to the first two and, as such, hardly comes into consideration here. The drag power affects flight direction, and the degree of freedom of movement associated with this direction causes practically no flight instability. /14
Non-compressible currents are a further limitation which must be assumed here in order to remain within the limitations of this short article.

The Prandtl Approximation of the Vorticity Equation

The classic statement for solving three-dimensional flow problems of airfoils is closely related to the name of Ludwig Prandtl.[1] He is to be thanked for the early recognition of the

[1] See also: P. Bublitz, "Unsteady flow mechanics," DFVLR-Nachrichten No. 37 (November 1982), pp. 24-29.

close relationship between induced drag and pressure dispersion on an airfoil together with its phase relationship to movement form. This drag results from the strength and diffusion of the vortex swirling behind the airfoil. The boundary condition of diminishing or at least tangential relative velocity on the surface of the body in the flow is tantamount to the continuing production of vortex swirl. In a flow free from compressible effects the vortex swirl vector is the physical dimension which rules the entire flow field. The vorticity equation resulting from the conservation of momentum theorem describes the convection and diffusion of the vortex swirl. This equation is a non-linear integral differential equation for the vortex swirl vector. For a number of reasons, it is inaccessible without meaningful physical approximations of a general solution. The classical Prandtl experiment of an airfoil wing moving out of a resting state can be explained through a very simple approximation of the vorticity equation. The author also used this equation in a later continuation of the theoretical description of the wake of oscillating airfoils having finite wingspan. Recently, this mathematical model was successfully tested in experiments. The duration times of sonic impulses were measured straight through the wake and compared with theoretical assertions. Several results will be presented at the end of this article which came about largely because of these assertions. All of the so-called exact potential theoretical solutions for non-compressible bodies in flow can be represented as approximations of the vorticity equation. At the same time, this equation makes it clear that they are not, indeed, exact, but rather include errors which may be precicely described. In each case one must decide whether or not they are acceptable.

If viscosity is overlooked, the conservation of momentum theorem leads to a first integral in the form of the Bernoulli equation and with it to a determination of pressure, but the decisive statement about the whereabouts of the vortex swirl produced simply cannot be obtained from the Laplace equation for the scalar potential of the velocity field. On the contrary, it is an unfortunate error, running through the course of aerodynamic history, that there is so much talk about frictionless flow. It is legitimate in many nonetheless technically very important cases to limit the boundary layer to thin sheets and then to use the mathematical instrumentation of the potential theory. First of all, however, one must understand these flows beset with vorticity. They result from the solution of the vorticity transport equation.

What we have called Prandtl approximation of the vorticity transport equation primarily may be defined using the following characteristics: /15

-- The increasing boundary layer around a profile is approached by an unchanged thin layer of vortex swirl.

-- The expansion of the whirling vortex swirl layer caused by diffusion is neglected, and the influence of the infinitely thin wake on the profile is considered to be a far field solution of a finitely thick vortex swirl layer.

-- The field-generating effect of the vortex swirl is suppressed with regard to its own deformation.

Figure 2 shows the geometric representation of a typical lift and wake foil as well as direction of the undisturbed oncoming flow u_∞ from the standpoint of a simultaneously moving observer.

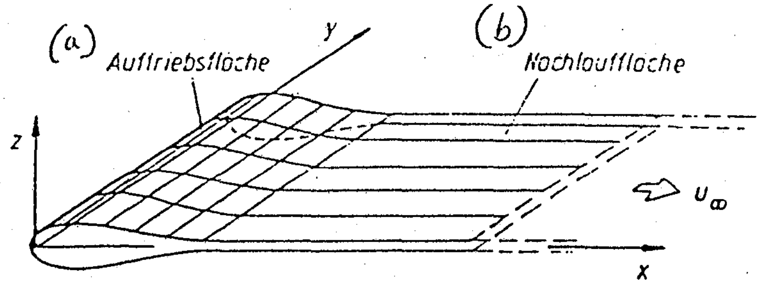


Figure 2: Geometric representation of (a) lift foil and (b) wake foil

Figure 3 outlines the course of the vortex swirl, as it results under control on a set plate of wingspan d and wing depth l. Not only the entire velocity field is determined by numerical determination of this vortex swirl dispersion, but also the pressure dispersion in all points of the flow field.

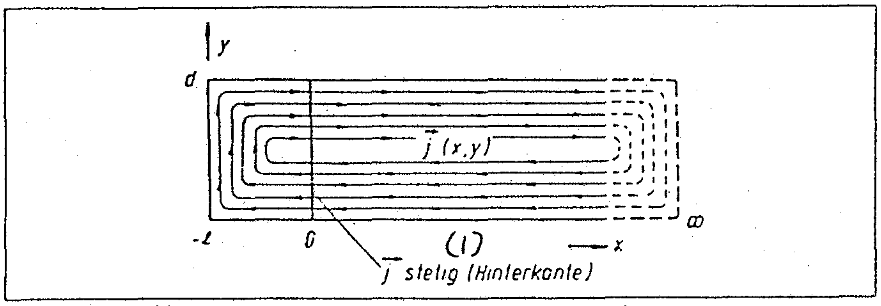


Figure 3: Vortex swirl vector of the plate solution for stationary flow, (1) constant (tail edge)

Unsteady wake

The first ideas on the configuration of unsteady wake were developed by L. Prandtl himself (Figure 4).

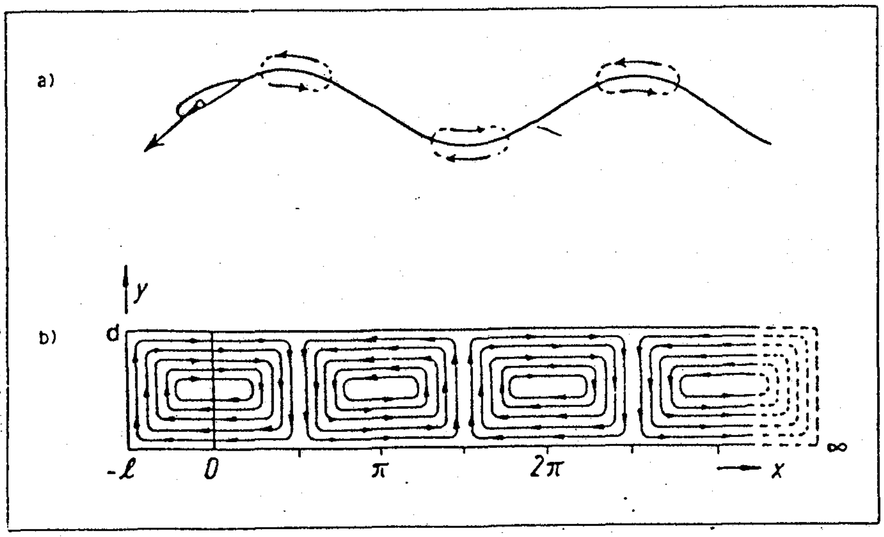


Figure 4: Unsteady wake of a profile, two-dimensional according to Prandtl (a), three-dimensional (b)

Figure 4a shows the cross section of a two-dimensional wake, as Prandtl introduced it at the hydro-aerodynamics conference in

Innsbruck in 1922. The works of W. Birnbaum on the even problem of the driving wing (1924) and of H. Wagner on the origins of dynamic lift (1925) rest de facto on the approximation of the vortex transportation equation which we call the Prandtl approximation. At that time, however, no experiments were undertaken to demonstrate the relationships in three-dimensional flow. An experimental study by S. Taneda dealt with the unsteady wake behind a circular cylinder in oncoming flow (1952). Figure 5 shows the results of his observations, which were preceded by extensive descriptions, through which he was able to derive velocity directions. Figure 4b outlines the dispersion of a vortex swirl in the wake of an oscillating airflow, as recently published by the author. If one places the thumb of the right hand in the respective direction of the integral curves, then the crooked fingers point in the direction of the local velocity field. Naturally, complete agreement cannot be expected, but it is plain to see, nonetheless, that the phenomena and ideas are closely related.

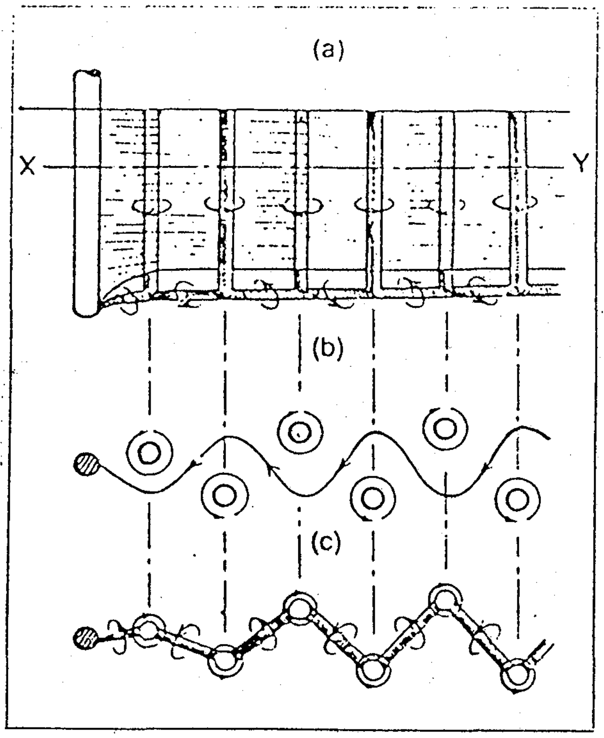


Figure 5: Wake behind a circular cylinder in oncoming flow (S. Taneda)

Figure 6 shows vortex swirl vector values using layered lines for a plate carrying out drive oscillations. It can be seen clearly that little vortex swirl occurs in the return point (φ = 0 degrees), while a high concentration of vortex swirl occurs on the plate foil when crossing the resting state (φ = 90 degrees). The trailing edge lies at x = 0. The effects of distinct boundary vortices diminish increasingly as the wingspan increases. With a boundary case of infinite wingspan one /16 obtains the classical two-dimensional solution in the cross section. This goes back to the findings of Kuessner (1936) and Theodorsen (1935). The solutions for successive impulse duration calculations are based on thick profile flows. Phase displacement between movement form (Figure 1c) and the corresponding pressure dispersion on the profile ultimately can be traced back to wake influence, more precisely to velocities on the profile induced by vortex swirls in the wake. The vortex swirls produced there must be just strong enough that their influence on each other, together with the influence of the wake, constantly lead to a tangential lift foil flow.

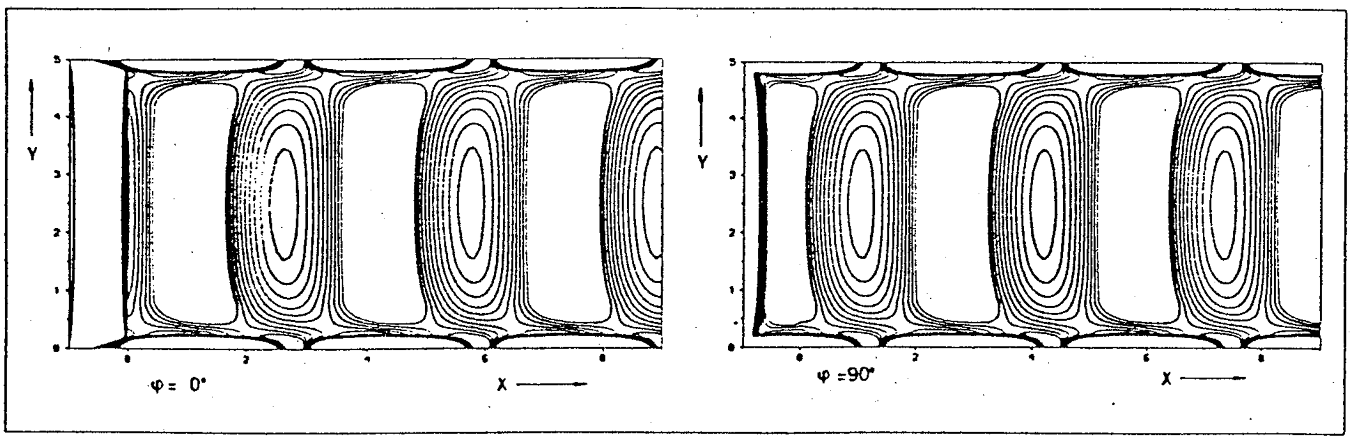


Figure 6: Strength of vortex swirl on lift foil and in wake of an oscillating plate at return point (φ = 0 degrees) and when crossing through resting state (φ = 90 degrees)

Induced drag is caused by pressure decrease on the airfoil's outer edge. Whirling vortex swirls cause this pressure decrease even in steady cases. The cross section of Figure 3 clearly shows that this wake influence is missing in two-dimensional boundary cases of steady flow. The influence of edge vortices on the solution in the symmetric line disappears as wingspan increases. The vortex swirl calculated in Figure 6 also shows that only cross vortices have any influence on the cross section when a moderate side ratio of d/l = 5 exists. These cross vortices occur, however, only in unsteady cases.

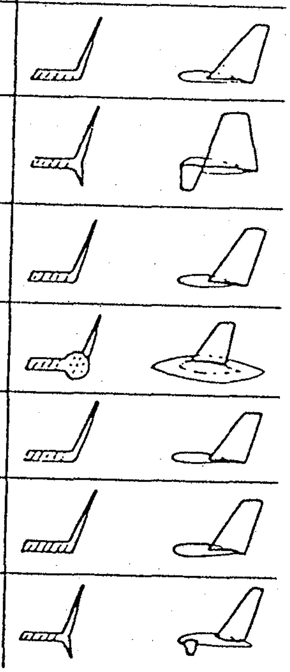
Technical Aspects

If one tries to ignore the cross vortices in Figure 6 and, at the same time, to enlarge the side ratio d/l, then an apparent paradox results, where the strength of the edge vortex is clearly not dependent upon the wingspan of the profile in which it was produced. In other words, the vortex's unavoidable, parasitic effect decreases in direct proportion to its replacement by lift and in indirect proportion to its increase in convecting thrust power. This use is limited practically only by the sinking stiffness and tenacity (of the rotor). This is the point at which even modern materials encounter limitations. Unsteady /17 air power, particularly in coupled drive and rotating oscillations, can lead to movement, which takes energy away from the air stream and leads to extreme amplitudes with unpleasant results. For stability investigations on aerodynamic systems, it is very important to have exact knowledge of unsteady air power and its causes.

To reduce the parasitic effect of the edge vortices, recent airfoil constructions of winged craft have once again involved fanning out airfoil ends. This is an effect known to us from observing the flight of birds.

U. Kueppers dealt with this subject in a very thorough and practical fashion.[2] Figure 7 is taken from his book, which depicts the rapidly increasing importance of this aspect of space technology in recent years.

(a) Flugzeugtyp	(b) Erstflug	(c) Wingletkonfiguration
Learjet 28/29	1977	
Arava IAI 202	1977	
Learjet 54/55	1979	
Westwind II	1979	
Gulfstream III	1979	
KC-135	1979	
DC-10	1981	



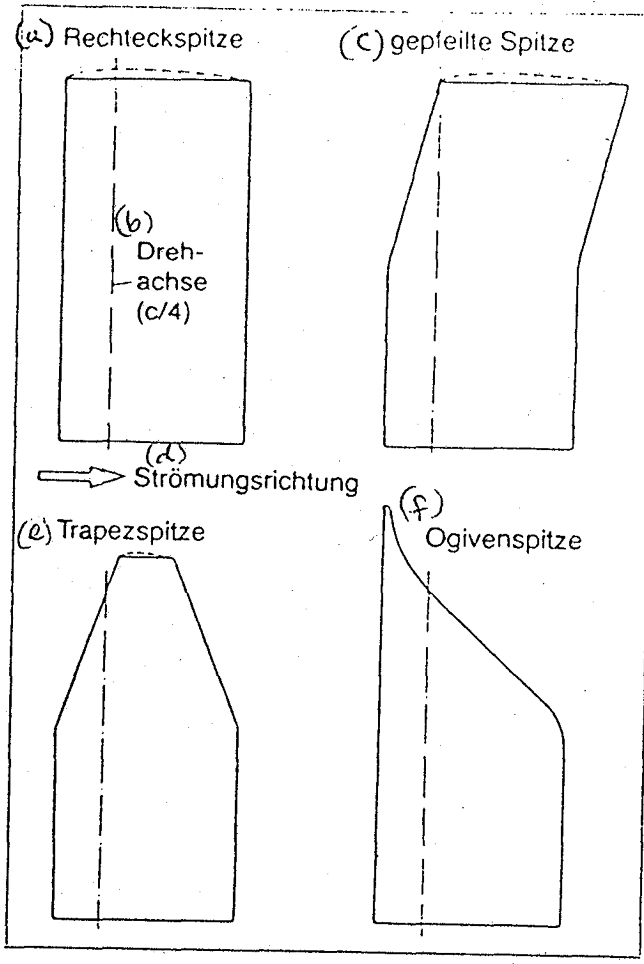


Figure 7: Winglets on aircraft with fixed wings (a) aircraft type, (b) first flight, (c) winglet form.

Figure 8: Blade tip forms for rotary blades (a) right angle tips, (b) rotating axle, (c) filed tips, (d) flow direction, (e) trapezoidal tips, (f) ogive tips.

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[2] Edge Vortex Dispersion through Fanned Out Wing Tips, VDI-Publishers, Duesseldorf, 1983

So-called winglets are becoming increasingly popular on aircraft with fixed wings. DVFLR itself, in cooperation with NASA at the Institute for Aeroelastics, has begun to investigate similar rotating lift systems. Figure 8 shows four blade tip forms, which have been investigated experimentally and theoretically. One additional difficulty with rotating systems defines narrow boundaries for the variety of blade tip forms. Unstable air forces and torques cause rotor disturbances affecting everything from the passenger compartment to stability. The contradictory forms needed for dispersion and flattening of edge vortex swirls, testify simultaneously to the elementary lack of theoretical knowledge, since not even tendencies can be predicted yet.

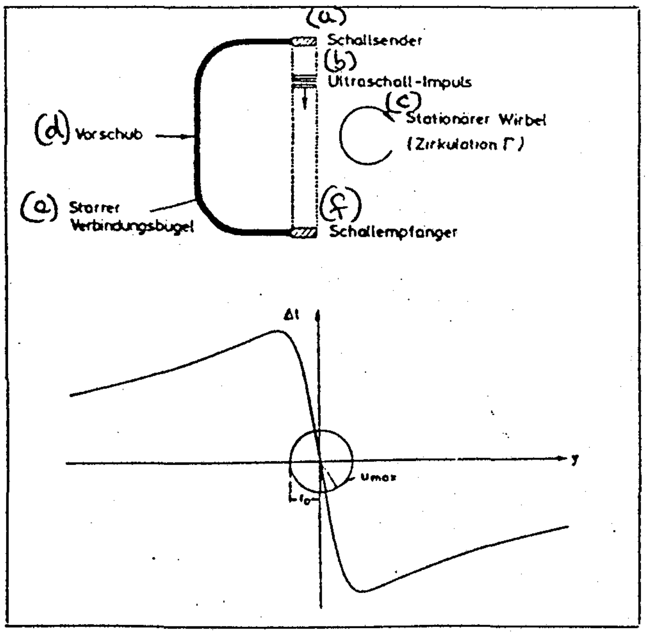

Figure 9: Principal of ultrasonic measurement
Key: (a) Wave transmitter, (b) Ultrasonic impulse, (c) Stationary vortex, clockwise circulation, (d) Thrust, (e) Rigid connecting curve, (f) Wave receiver

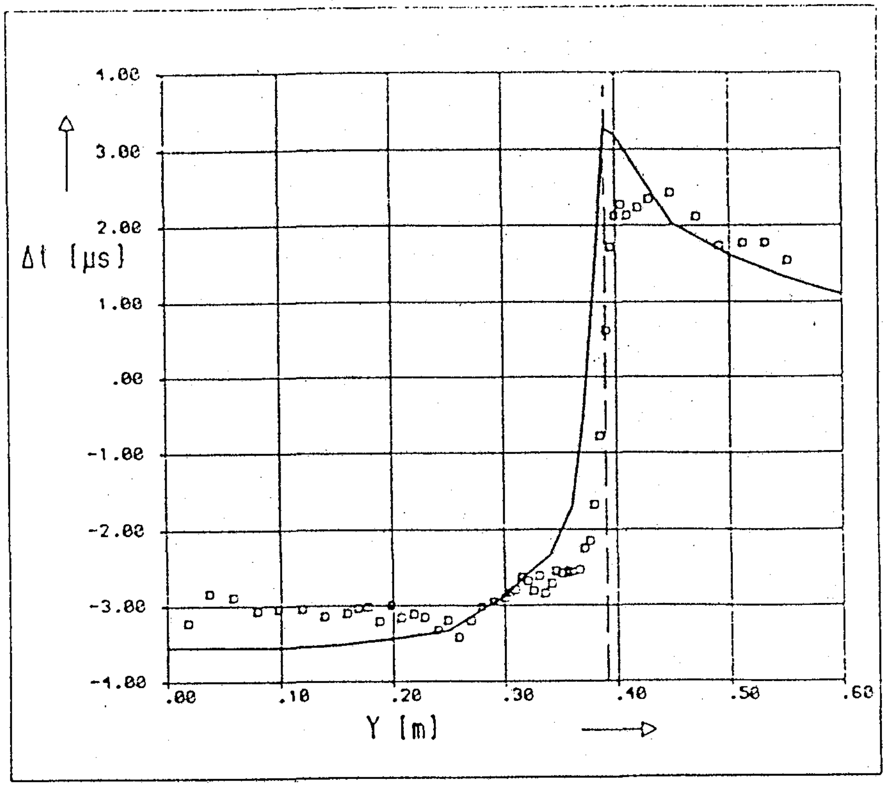

Figure 10: Pulse timing behind a profile with 8-degree incline (Solid lines indicate theory, outlined boxes indicate experiment, dotted lines indicate edge)

A further effect would be lessened by the dispersion of edge vortex swirls which occur as each successive blade cuts through the vortex trail of the preceding one: Excessive noise levels connected with certain flight situations would decrease and help to eliminate related problems. For example, bombardment of the vortex core by successive airfoil edges causes dynamic tip loads. The effects of such bombardment on the passenger area has limited the uses of the helicopter to this day.

Comparison between Theory and Experiment /18

Tests of mathematical models of unsteady wake are dependent upon the capacity to determine the time progression of undisturbed velocity fields. Today there are two procedures which may be used:

1. Laser-Doppler-Anemometry
2. Ultrasonic-Anemometry

Research is being done in Goettingen on both procedures. The second procedure is based on convection of wave signals into flow. R. Engler of DFVLR Wind Tunnel Division developed this measuring technique several years ago at the Max Planck Institute for Research on Stationary Flows. Recently, my colleague, W. Wagner, was successful in applying this technology to measuring unsteady flows. Figure 9 shows the measuring principal. An ultrasonic impulse is sent out and its duration measured. At a pulse length of 0.5 m (curved wingspan) this always amounts to about 0.0015 s. A change of velocity in pulse direction--about perpendicular to the vortex--results in a tiny pulse time difference Δt. Their dimensions differ by microseconds. Figure 9 outlines the prinicpal course of Δt when the measuring curve is forced into a position perpendicular to a specific vortex. Figure 10 shows the impulse duration differences measured by R. Engler. These measurements extend from the wing's midsection ($y = 0$) to beyond the edge six wing depths behind a NACA-0010-profile. The pitch angle amounts to $\alpha = 8$ degrees. With reference to Figure 3 the curved axis stands about perpendicular on the intended wake level. Similar measurements were made against the stream and verify that the theoretical model comes very close to reality. Figure 11 shows an unsteady measurement (W. Wagner) a half wing depth down stream behind a NACA-0012-profile. The variation of impulse duration difference over the periods of a rotating oscillation is recorded. The measuring position in wing width y is an extension of the edge y_R half a wing depth outside ($y = y_R + 1/2$) and/or inside ($y = y_R - 1/2$) of edge and of wake foil. Stationary pitch amounts to $\alpha = 5$ degrees and amplitude of rotating oscillation $\Delta\alpha = 1$ degree. The evaluation requires a high degree of accuracy in measuring technique as well as in numerical evaluation of the mathematical model. Linear theory boundaries in the solution as it concerns amplitude can be seen in Figure 12. At pitch angle α = 0 degrees amplitude amounts to $\Delta\alpha$ = 8 degrees. At this high amplitude, the wake deforms and turns into a wavy foil. The theory deviates considerably from the experiment. The organization of both measuring positions is analogous to Figure 11, but this time 1-3/4 wing depths downstream.

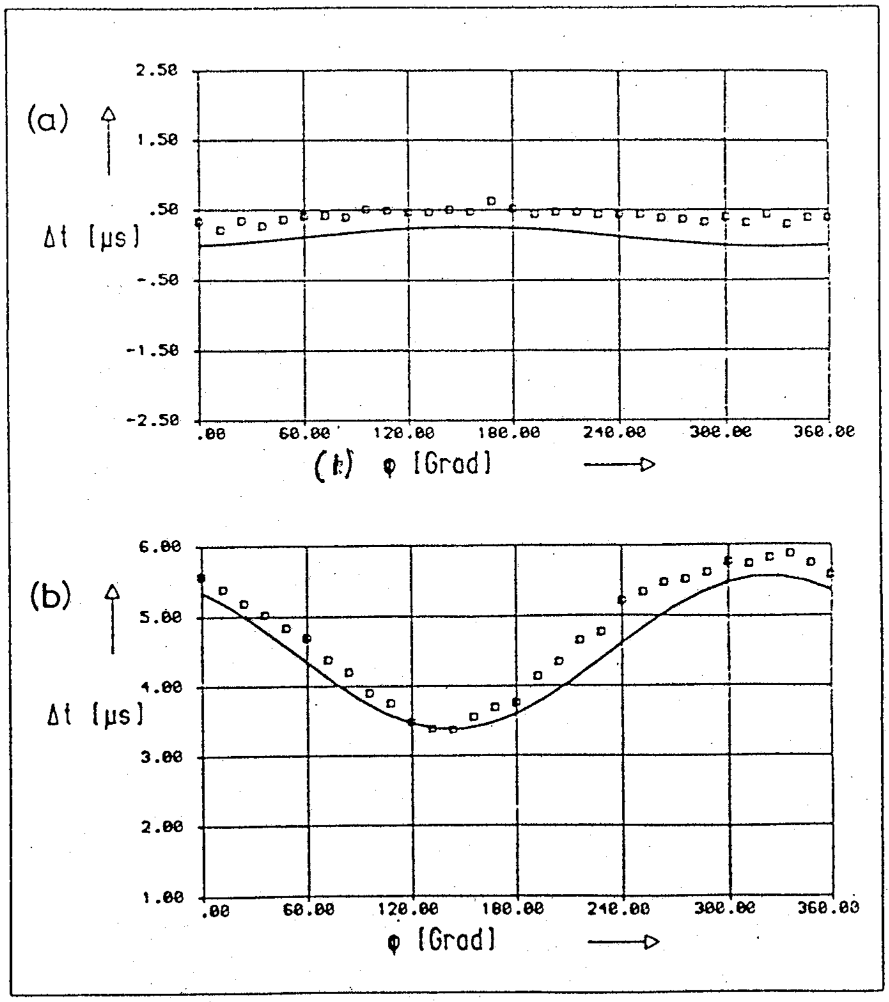

Figure 11: Impulse duration difference in wake outside (a) and inside (b) wake foil, low amplitude $\Delta\alpha$ = 1 degree (solid lines = theory, outlined blocks = experiment) (1) degree

Outlook

Considering the small part which airfoil theories play in aircraft development, theoretical models currently supply, both qualitatively and quantitatively, a precise idea of the dispersion of vortex swirls in a wake and their effects on the airfoil. The demand for optimum airfoil ends and blade tip forms has become increasingly significant from energy and construction sources. It is among the truly exciting tasks confronting aeronautics researchers in the near future to delelop refined models for the promising predictions. If one considers that a substantial portion of an aircraft's propulsion disappears in the edge vortices, then it will be realized how vital it is to eliminate this waste of energy.

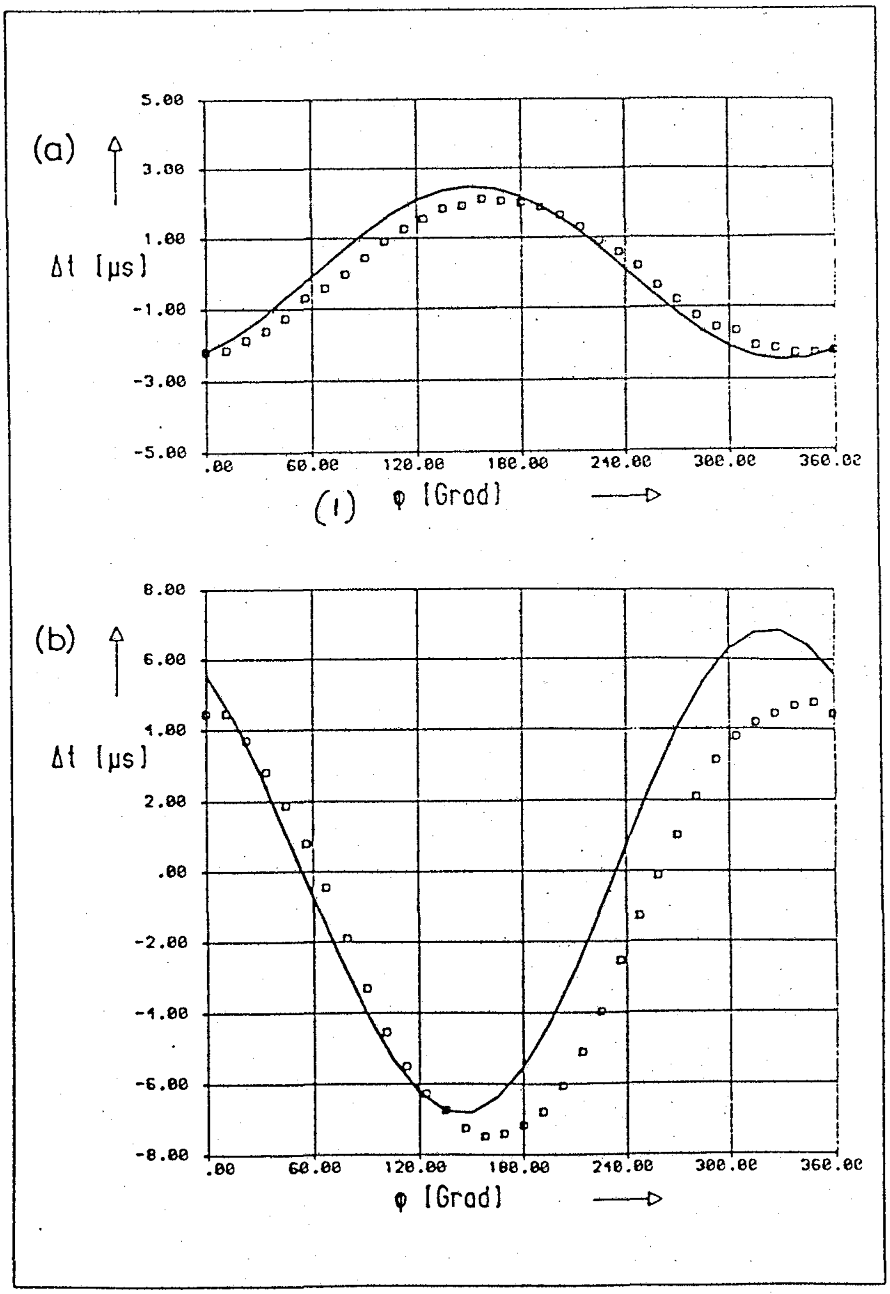

Figure 12: Impulse duration difference in wake outside (a) and inside (b) wake foil, large amplitude $\Delta\alpha$ = 8 degrees; Boundary of linear theory recognizable (solid lines = theory, outlined blocks = experiment) (1) degree