J. Szantyr – Lecture No. 21 – Aerodynamics of the lifting foils

Lifting foils are important parts of many products of contemporary technology.

< Helicopters

Aircraft

Gliders

Sails >

< Keels and rudders

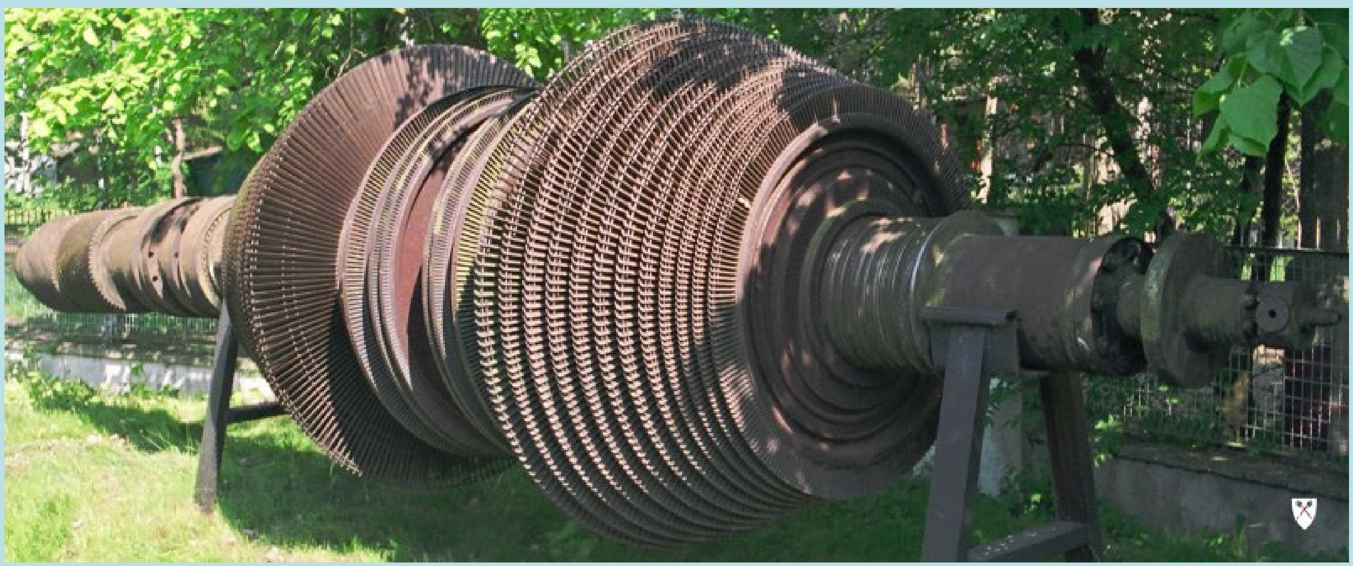
Hydrofoils

Ship propellers

Airscrews

Water turbines >

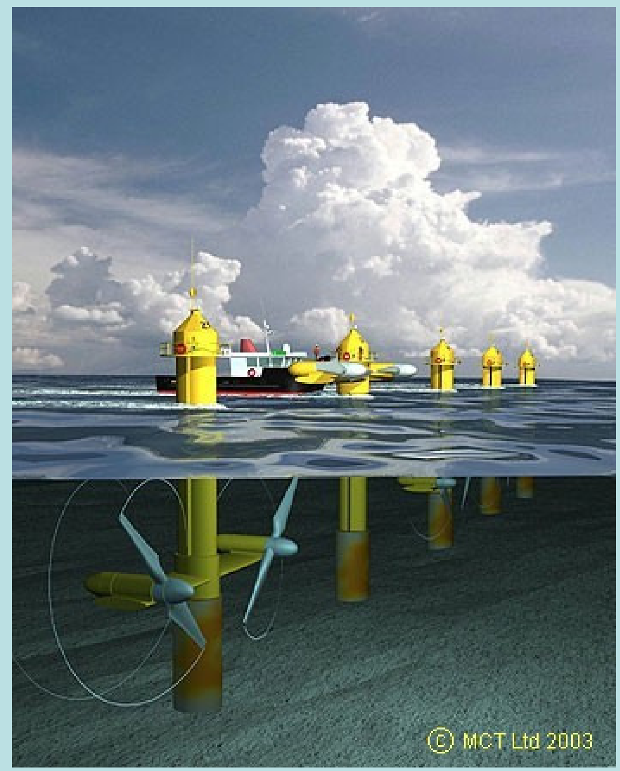
Steam turbines >



Racing cars

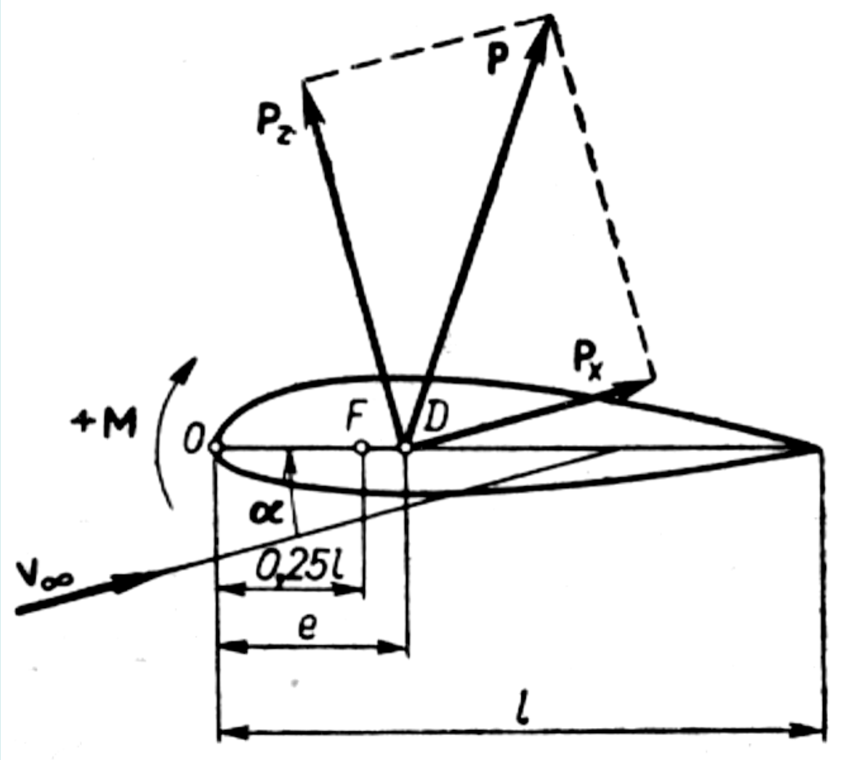
< Pumps

Wind and water turbines >



Nature always was and still is an inspiration for technology.

Aero- or hydrodynamic force is generated on any object placed in a flow. This force may be decomposed into a component perpendicular to the flow velocity, called **the lift force** and a component parallel to the velocity of flow, called **the drag force**. **The lifting foils** are objects shaped in such a way that the **maximum lift force and minimum drag force** are attained. The characteristics of the foil depend to a large degree on the geometry of its cross-section perpendicular to the foil span, i.e. on the geometry of **the aerodynamic profile.**



P – the resultant aerodynamic force

P_Z - the lift force

P_X - the drag force

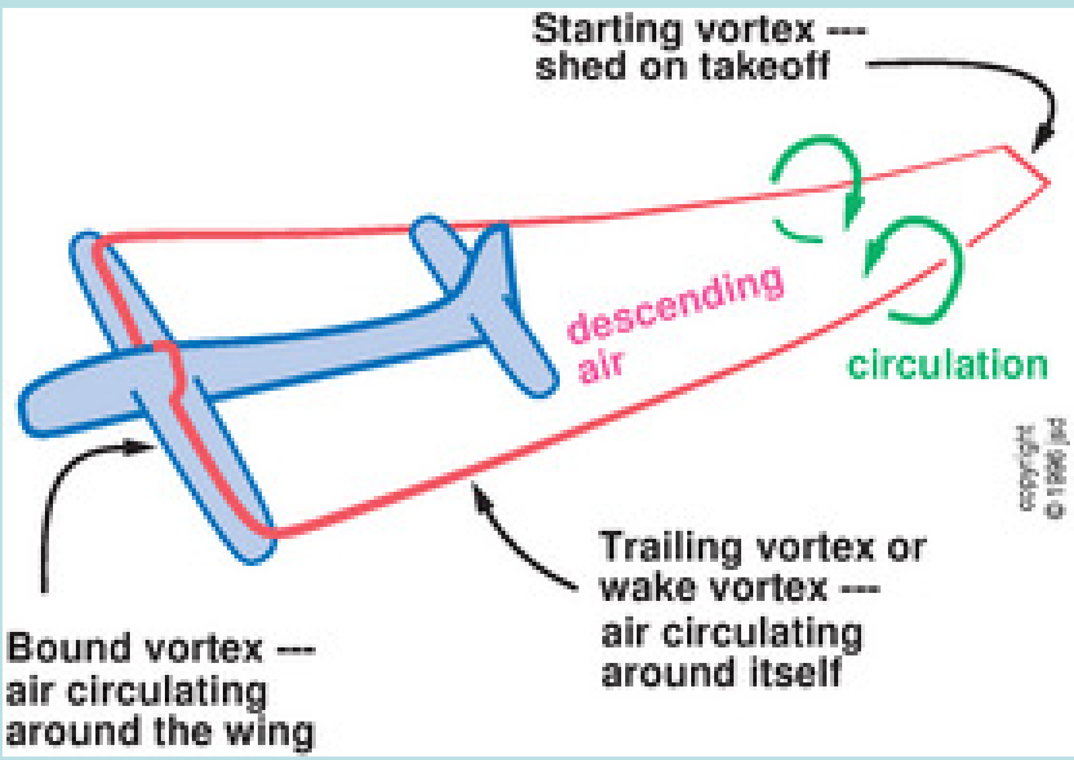
M – the moment of the aerodynamic force

V_∞ - the flow velocity

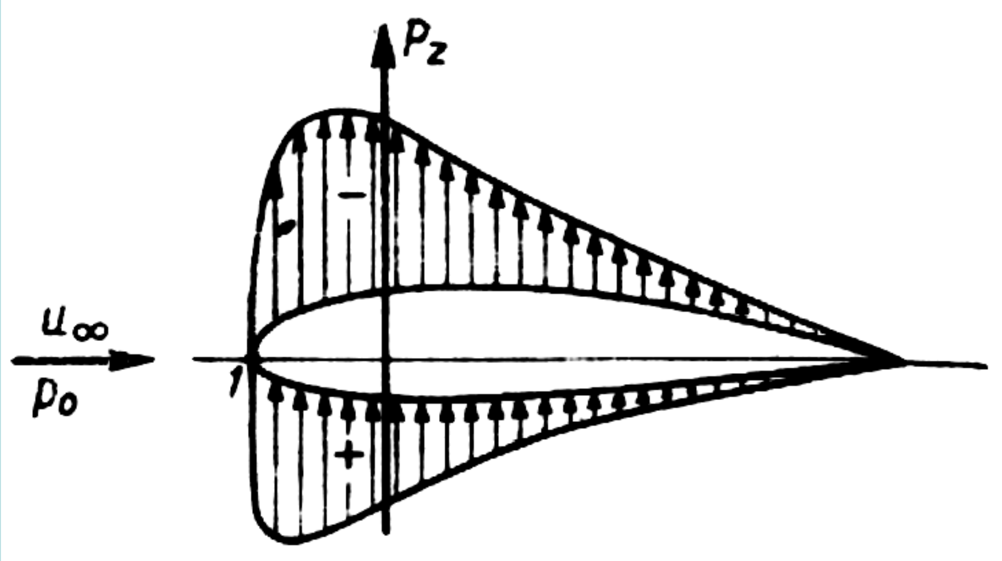
α – the angle of attack

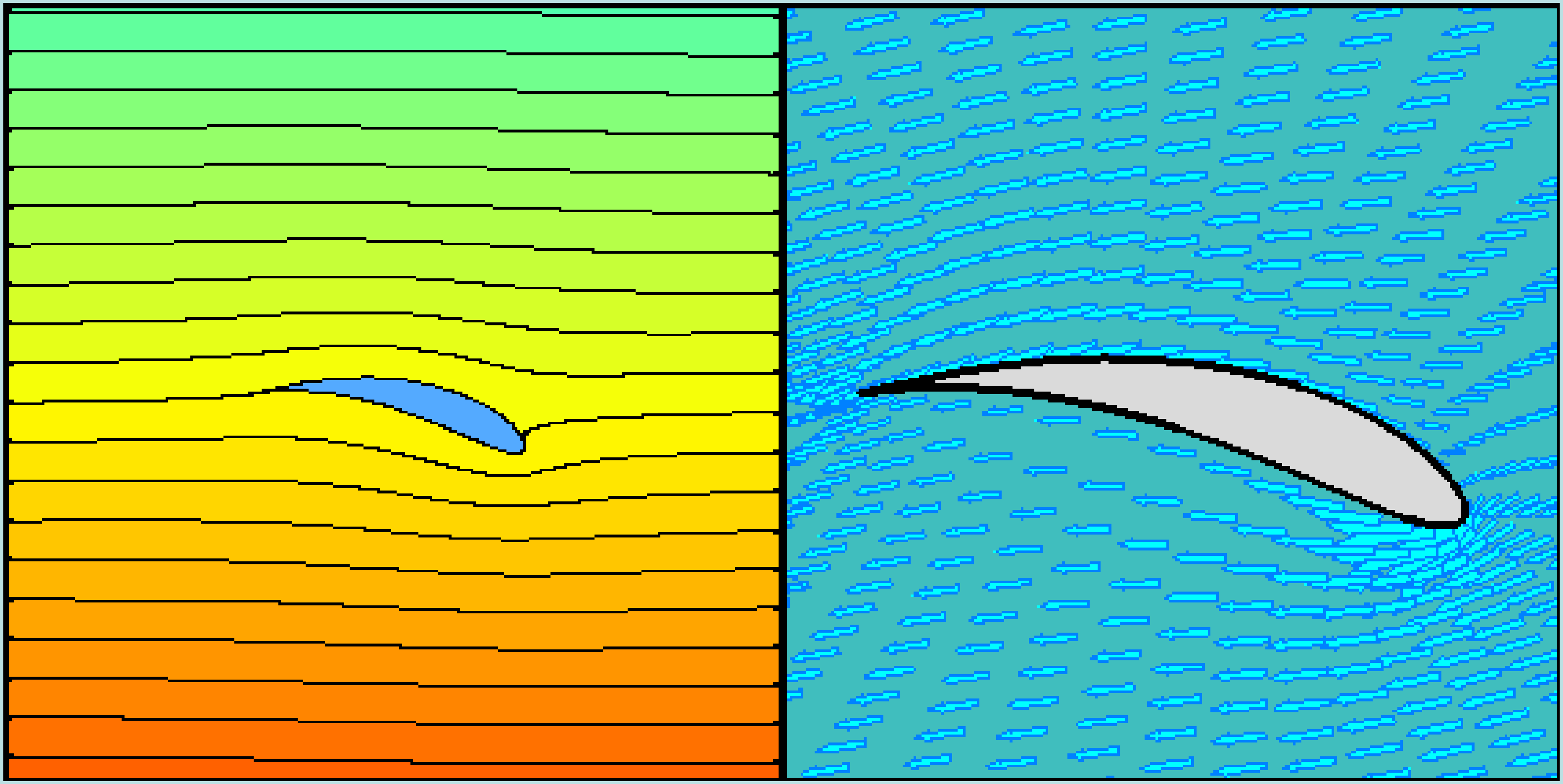
The point of action of the resultant aerodynamic force D changes its location with changing angle of attack, but as a rule it stays near the point F located at the distance 0,25 *l* from the leading edge, which is called the aerodynamic centre of the profile.

The real flow around a lifting foil may be modelled mathematically by means of a vortex:



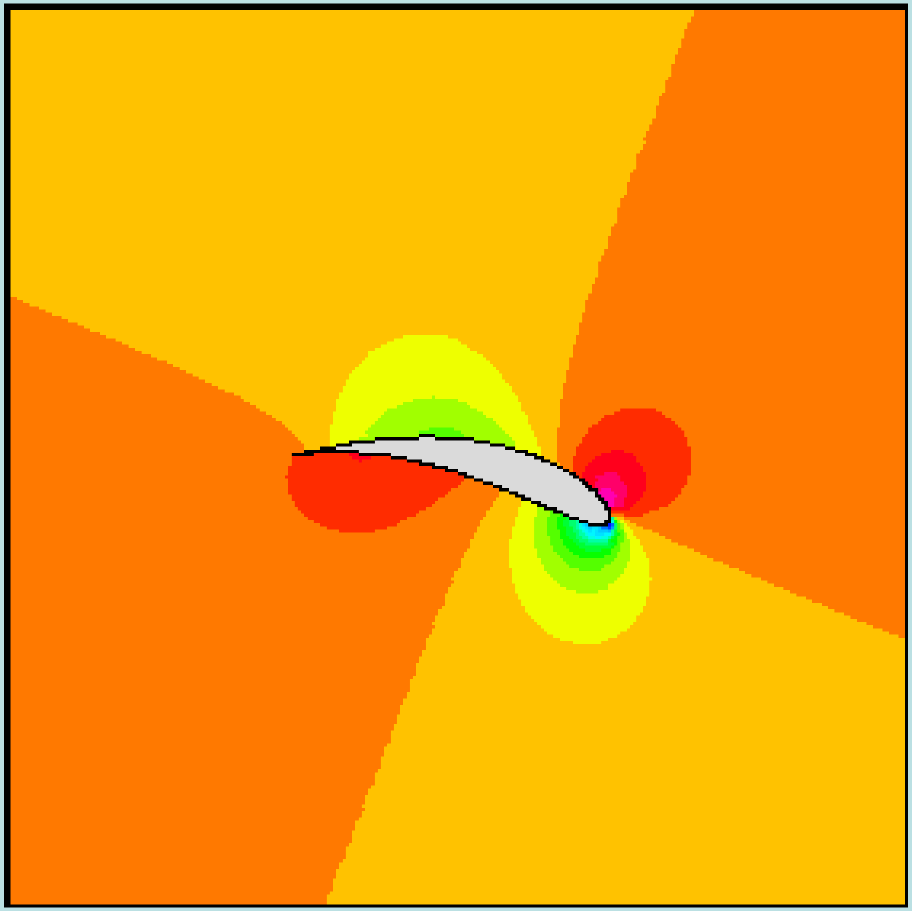
In order to produce the lift force on an airfoil it should be shaped in such a way that a **circulatory flow** is generated, i.e. the flow is asymmetrical with respect to the direction of the inflow velocity. Then on one side of the profile the velocity of flow increases and simultaneously pressure falls (this is so called **suction side**), and on the other side the velocity of flow decreases and simultaneously the pressure rises (this is so called **pressure side**). This pressure difference, acting on the profile generates the lift force. The circulatory flow is achieved either through cambering the airfoil or by setting it at a certain angle with respect to the flow velocity, called the angle of attack. In most cases the appropriate combination of both methods is used.



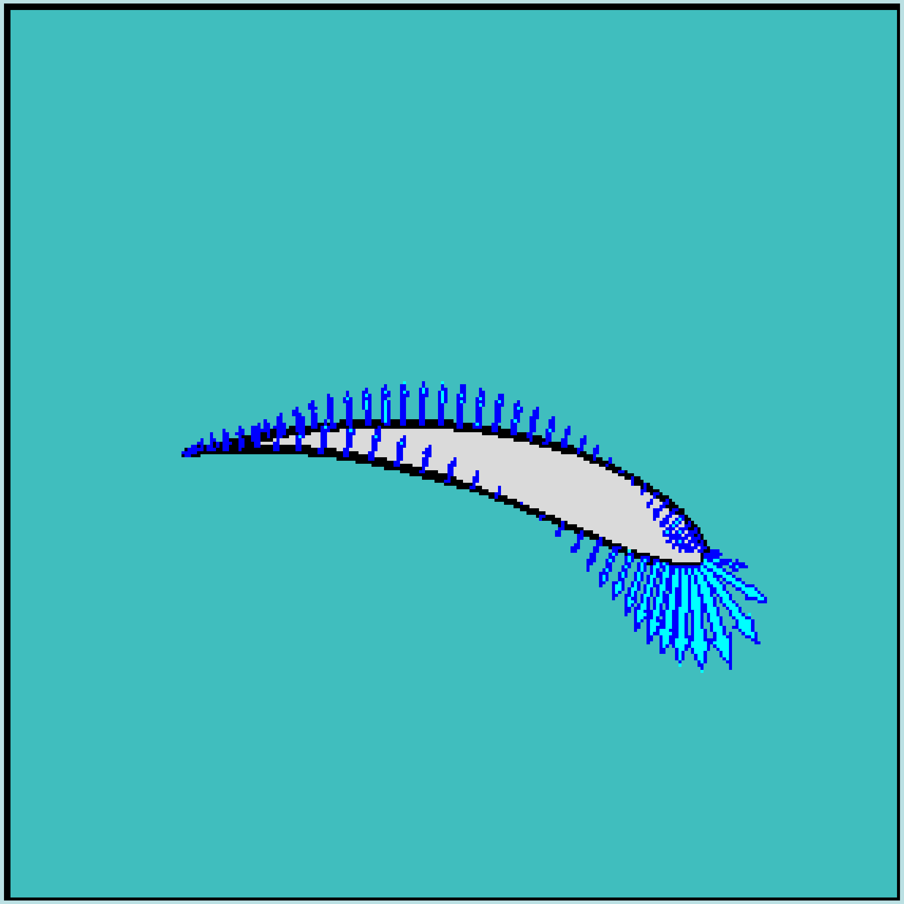


Stream-lines in the flow around a profile

Velocity vectors in the flow around a profile

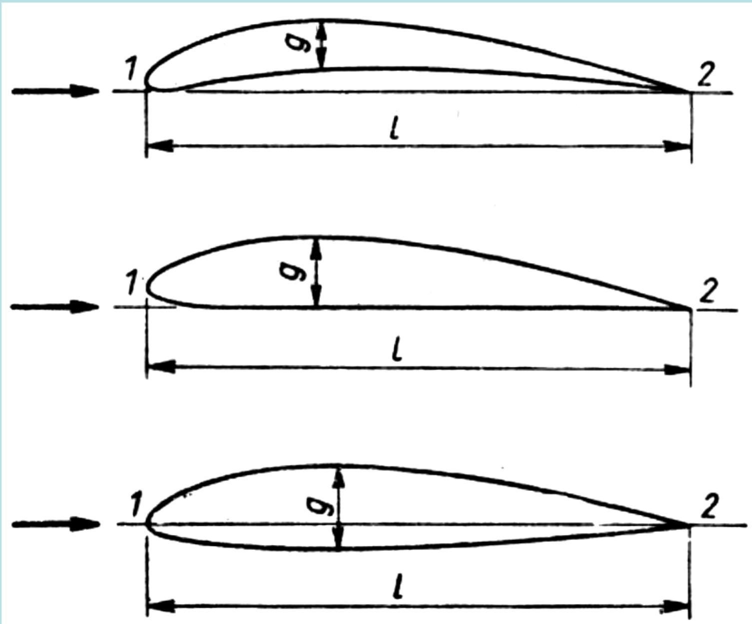


Pressure distribution on a profile at the changing angle of attack



Distribution of the elementary surface forces on a profile at the changing angle of attack

Geometry of the aerodynamic profiles

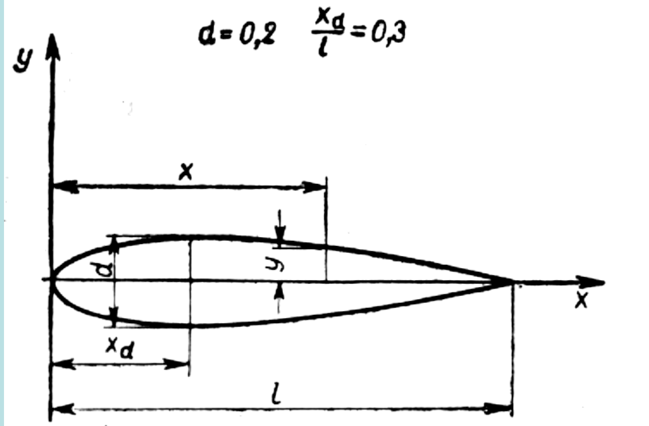


The profiles may be convex-concave (upper sketch), flat-convex (middle sketch), double-convex (lower sketch).

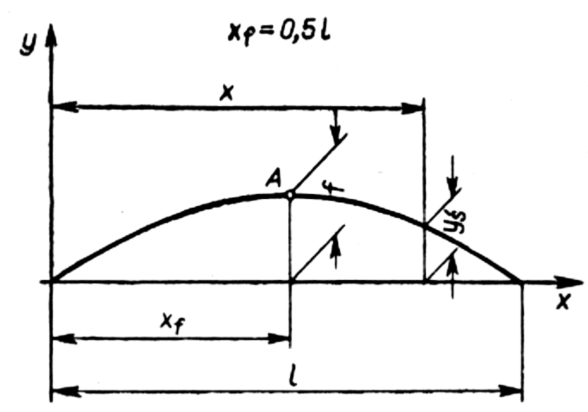
Profile chord *l* is the distance between the two most distant points of the profile.

Profile thickness *g* (or *d*) is the largest distance perpendicular to the chord limited by the profile contour.

The profile shape may be generated by an appropriate superposition of the symmetrical profile and the so called mean line.

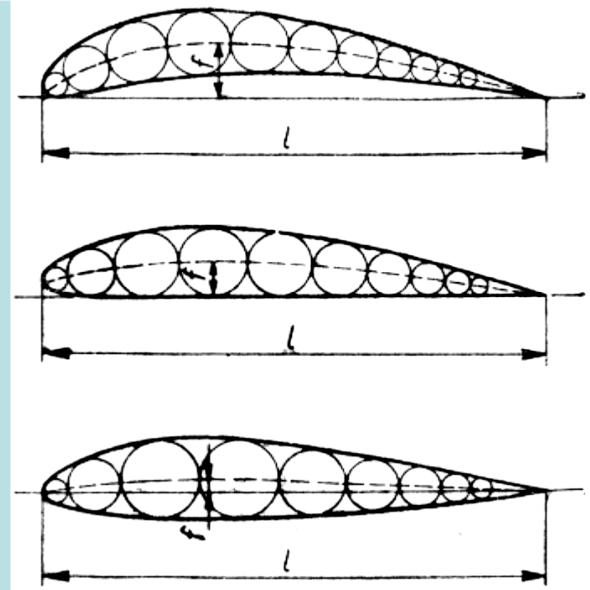


wyjściowy profil symetryczny



linia szkieletowa

Mean line is the geometrical location of the centres of circles inscribed into the profile contour.



Maximum camber of the mean line f and its location along the chord x_f are important parameters.

Another important parameter is the location of the maximum thickness x_d

Experimentally determined characteristics of the several families of airfoils with systematically varied parameters are available.

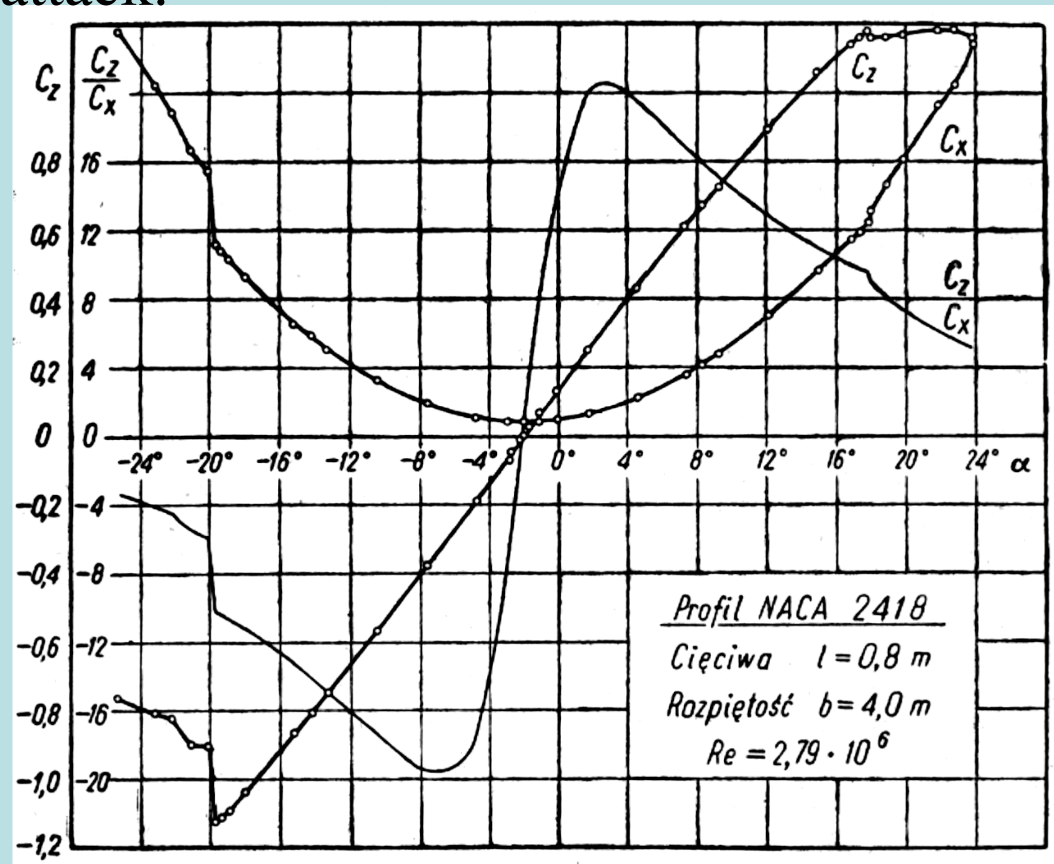
The best known is the NACA profile family (National Advisory Committee for Aeronautics – currently NASA):

Four digit series, eg. NACA2418: $$NACA\left[\frac{f}{l}100\right]\left[\frac{x_f}{l}10\right]\left[\frac{d}{l}100\right]$$

Five digit series, eg. NACA23012: $$NACA\left[\frac{f}{l}100\right]\left[\frac{2x_f}{l}100\right]\left[\frac{d}{l}100\right]$$

Aerodynamic characteristics of an airfoil

The aerodynamic characteristics of a profile include the dependence of the lift and drag coefficients (possibly also moment) on the angle of attack.



$$C_Z = \frac{P_Z}{\rho/2\, V_\infty^2 S}$$

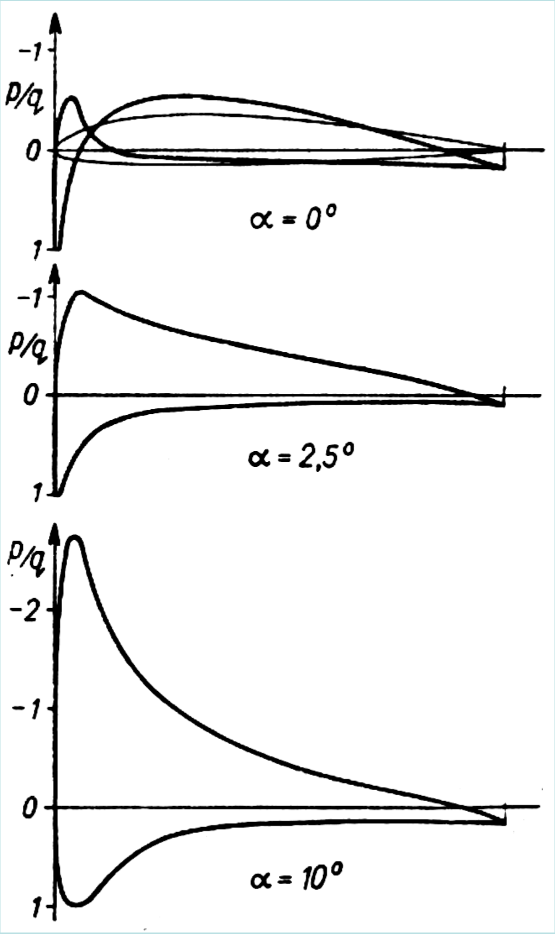
$$C_X = \frac{P_X}{\rho/2\, V_\infty^2 S}$$

$$C_M = \frac{M}{\rho/2\, V_\infty^2 S l}$$

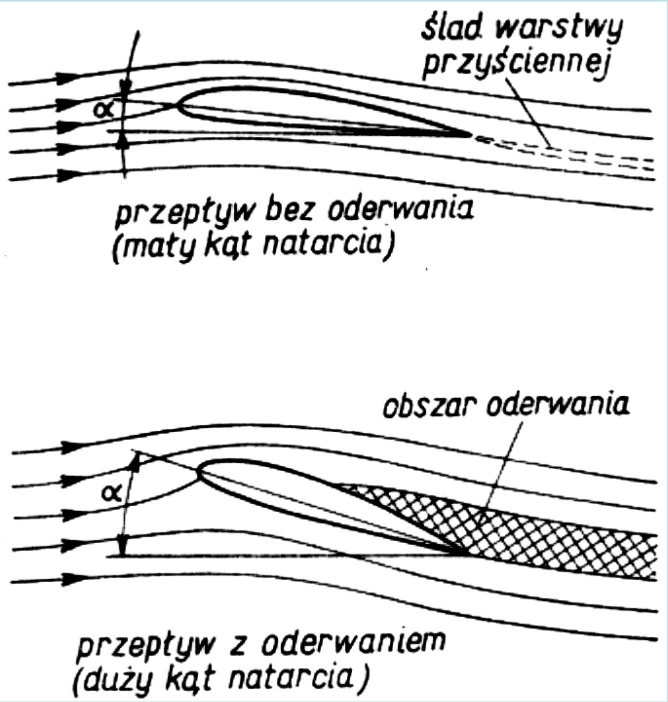
$$\varepsilon = \frac{C_Z}{C_X}$$ coefficient of the profile efficiency

where S – foil surface area (in case of a profile – the area of the foil section of unit span)

The form of the aerodynamic characteristics is reflecting the changing conditions of flow around the profile, resulting from the changes in the angle of attack. Moreover, it depends on the profile geometry, Reynolds number and Mach number.



At moderate angles of attack the lift force is a linear function of the angle of attack.



At high angles of attack the flow separation occurs and the lift force does not grow any further despite increasing angle of attack.

Some particular points of the aerodynamic characteristics are important:

Zero lift angle is proportional to the relative camber of the profile mean line:

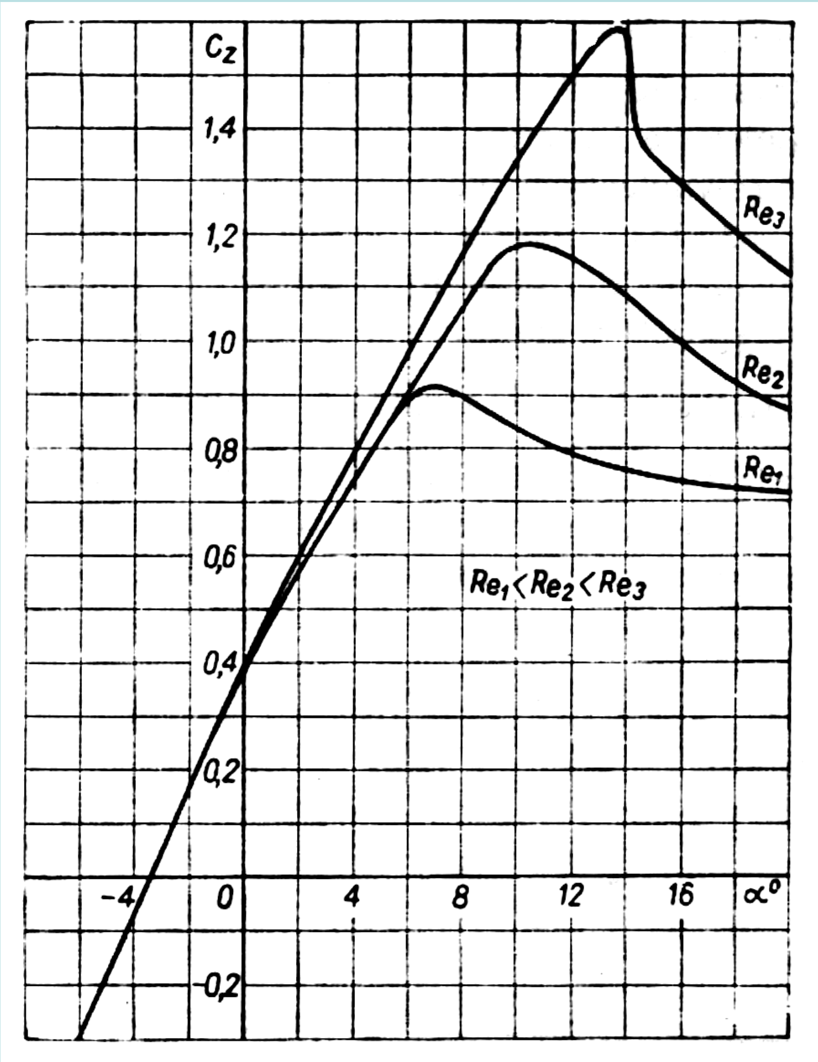
$$\alpha_0 = k \cdot \frac{f}{l}$$

Maximum lift angle (critical angle of attack) corresponds to the occurence of the developed flow separation on the suction side of the profile. For the profile NACA2418 we have:

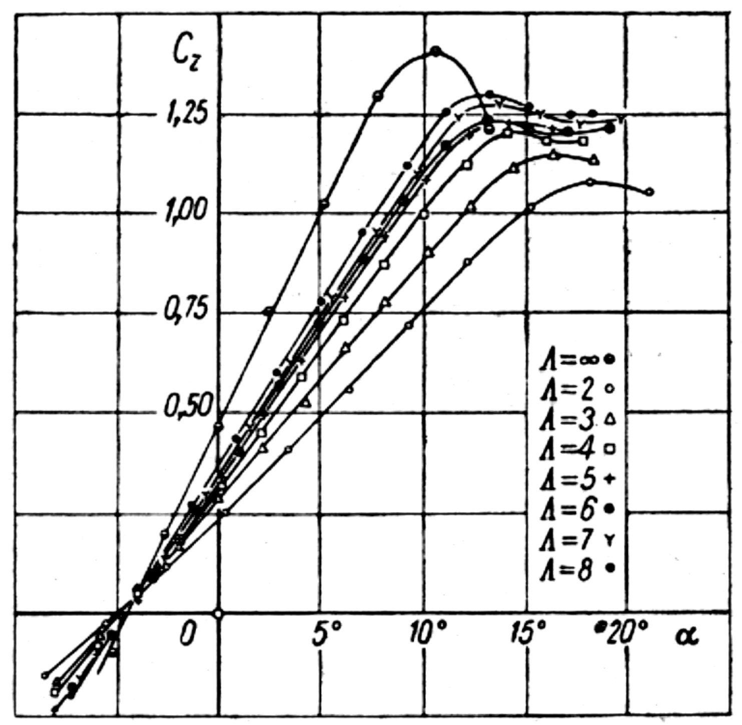
$$\alpha_{kryt} = 17{,}8^0$$

Optimum angle of attack corresponds to the maximum efficiency of the profile. For the profile NACA2418 we have:

$$\alpha_{opt} = 2{,}6^0 \qquad \varepsilon = 20{,}6$$



The maximum lift coefficient reaches higher values at higher Reynolds numbers, because then the separation of flow occurs at higher angles of attack.



When the aerodynamic characteristics are determined for the foil of finite span, the foil aspect ratio λ is the parameter strongly influencing the form of the characteristics:

$$\lambda = \frac{b^2}{S}$$

where: *b* – the foil span

If the foil aspect ratio λ is smaller, then the inclination of the lift curve is also smaller and so is the maximum value of the lift coefficient. This results from the increasing effect of the secondary edge flow, which leads to the equilization of pressure difference between the suction and pressure sides of the foil in the regions close to the edges. The value marked $\lambda = \infty$ denotes the aerodynamic characteristics of the profile.

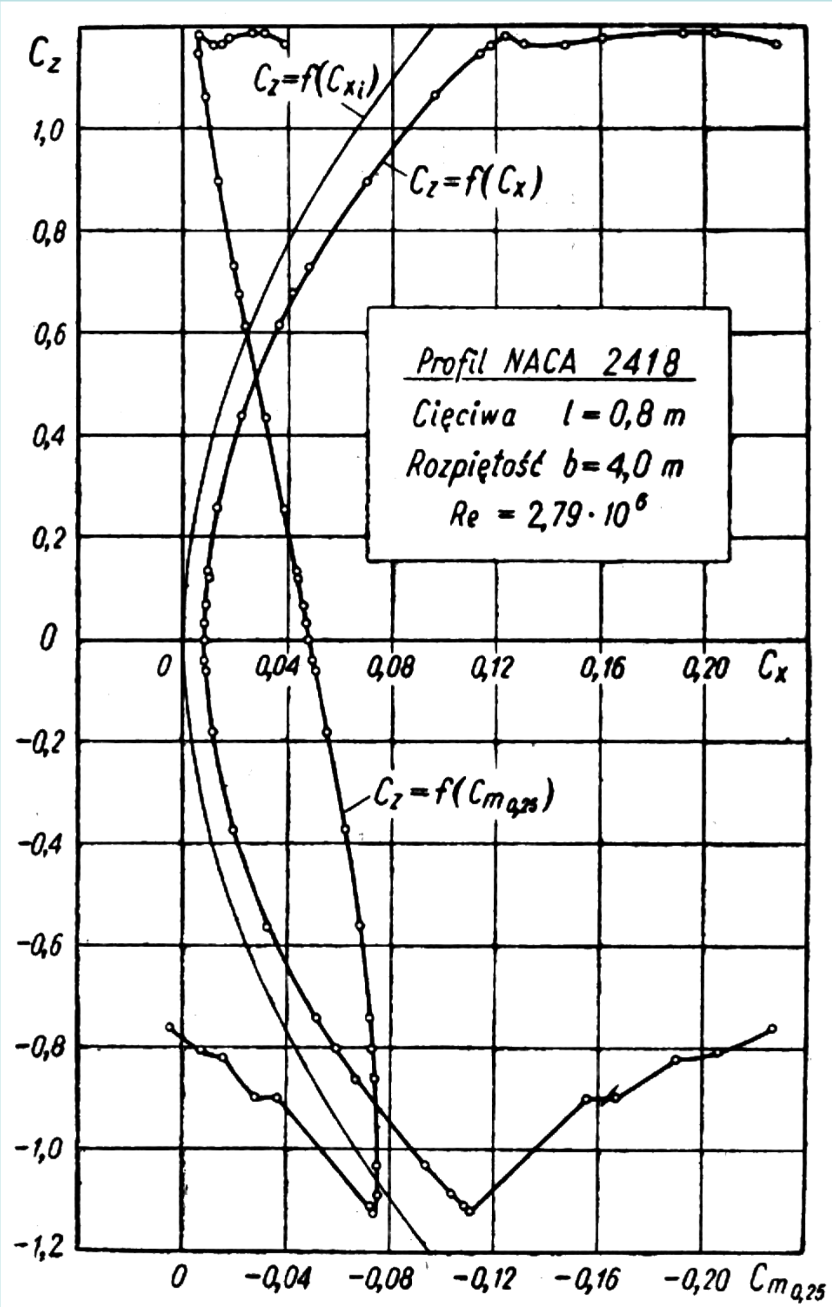
On the basis of known aerodynamic characteristics of a profile the characteristics of the finite span foil built of such profiles may be determined. For example for the rectangular outline foil we have:

$$\alpha = \alpha_{\infty} + \frac{C_z(1+\tau)}{\pi\lambda}$$

$$C_x = C_{x\infty} + \frac{C_z^2(1+\delta)}{\pi\lambda}$$

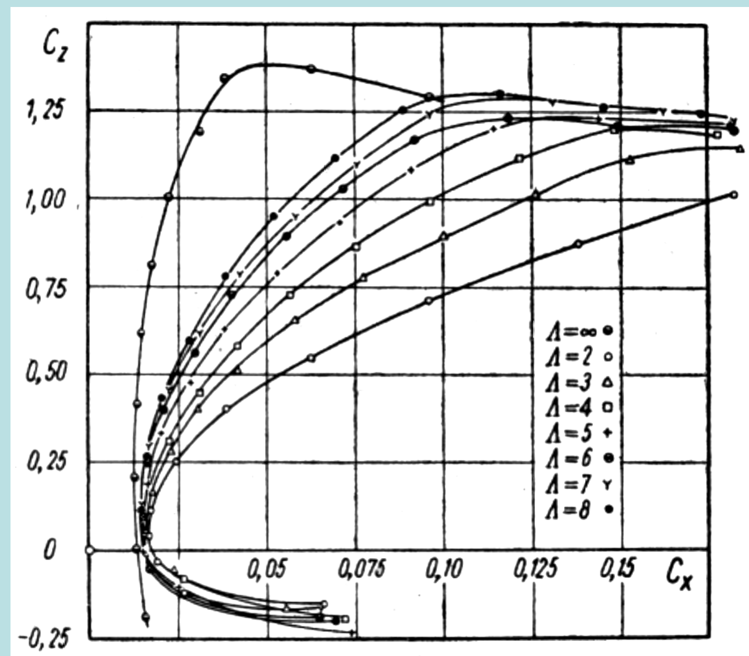
λ	τ	δ
3	0,11	0,022
4	0,14	0,033
5	0,16	0,044
6	0,18	0,054
7	0,20	0,064
8	0,22	0,074
9	0,23	0,083

With the known lift coefficient and angle of attack of the profile the formula 1 enables determination of the angle of attack of the foil of given span producing the same lift. Formula 2 enables determination of the drag coefficient of the foil at this attack angle, if the profile drag coefficient is known.



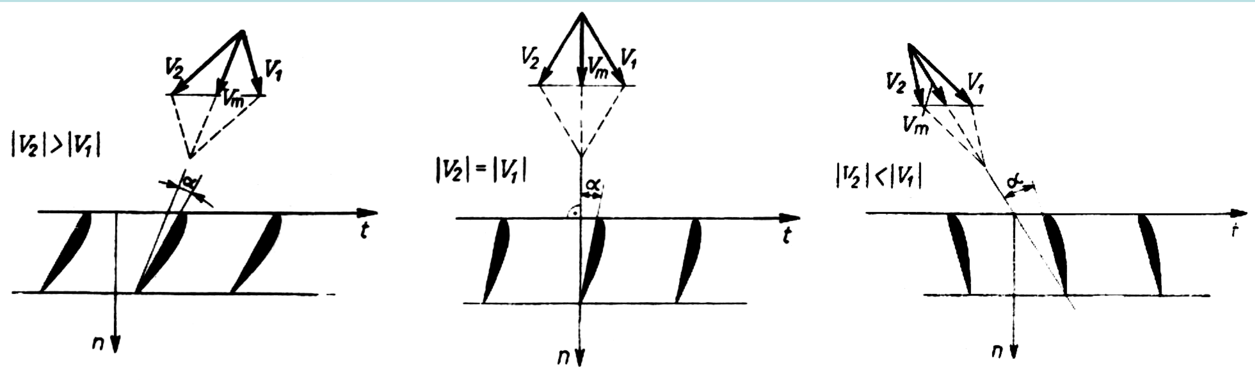
The aerodynamic characteristics may be presented in the form of the so called **polar diagram**.

In such a diagram the influence of the foil aspect ratio on the characteristics may be also presented



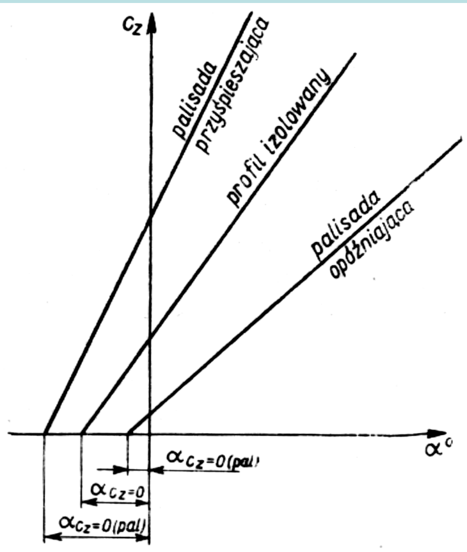
Cascades of profiles

Lifting foils forming eg. turbine or pump rotors interact with each other, changing their characteristics. This phenomenon may be analysed on the basis of so called cascade of profiles.



inflow velocity - V_1

outflow velocity - V_2



Accelerating cascade – the velocity at outlet is higher than the velocity at inlet (reaction turbines)

Neutral cascade – modules of the inflow and outflow velocity are identical (impulse turbines)

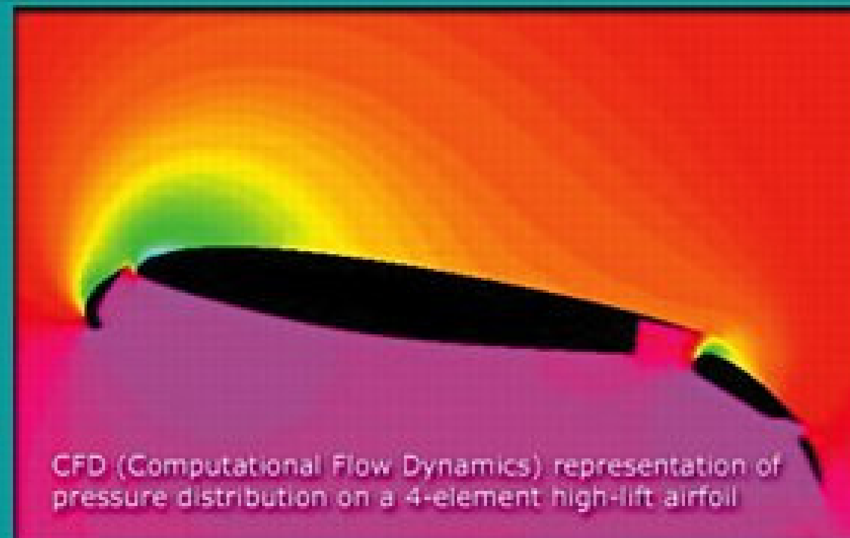
Decelerating cascade – the velocity at inlet is higher than the velocity at outlet (pumps)

High lift devices (mainly on aircraft) are used for increasing the lift coefficients at low velocities by changing the profile geometry (mainly increasing their camber).

A variety of devices on the wing's leading and trailing edges allow large jets to fly through a huge variety of conditions.

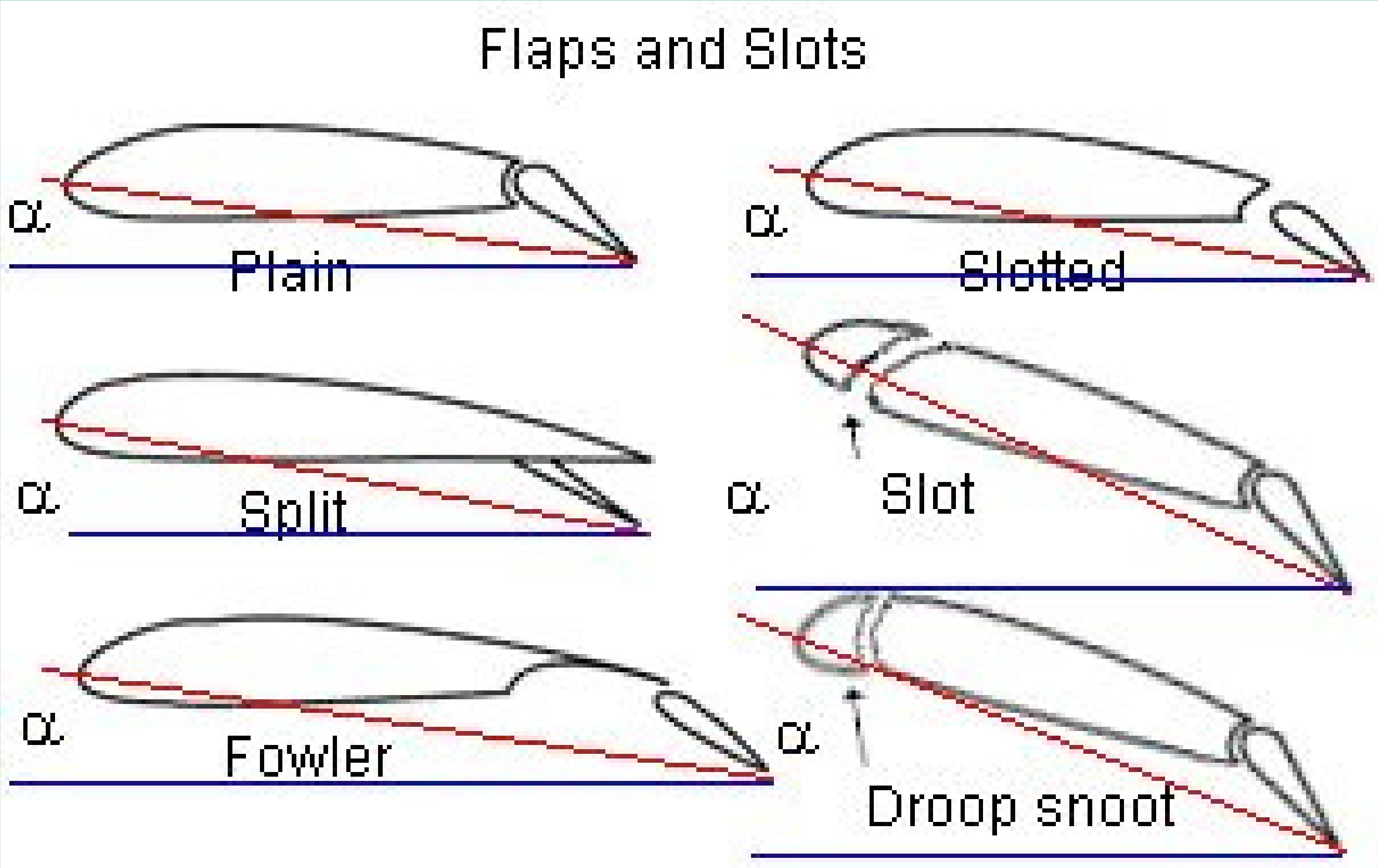
A big jet might take off at 140 knots, with full fuel and/or cargo, in poor weather, accelerate to 450 knots while climbing to 30,000 feet, cruise there for many hours, then return to the lower airspeed and altitude, for landing.

Without all the high-lift devices, the cruise-optimized wings could not do their job. Spoilers have several roles in these designs too, including the controlling of wingtip vortices. (more later)

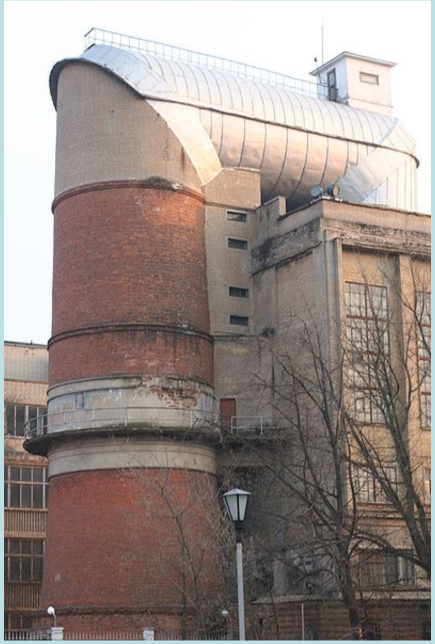


CFD (Computational Flow Dynamics) representation of pressure distribution on a 4-element high-lift airfoil

Different high lift devices on aircraft wings



Experimental testing and observations of air flow around different objects are performed in wind tunnels

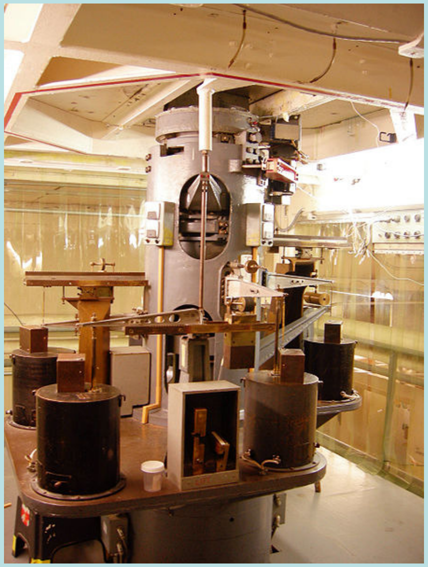


A large wind tunnel in Moscow (CAGI) →

← External view of a wind tunnel

← Inside of the wind tunnel measuring section

Six-parameter dynamometer for measuring forces on a model →



Different experiments performed in wind tunnels