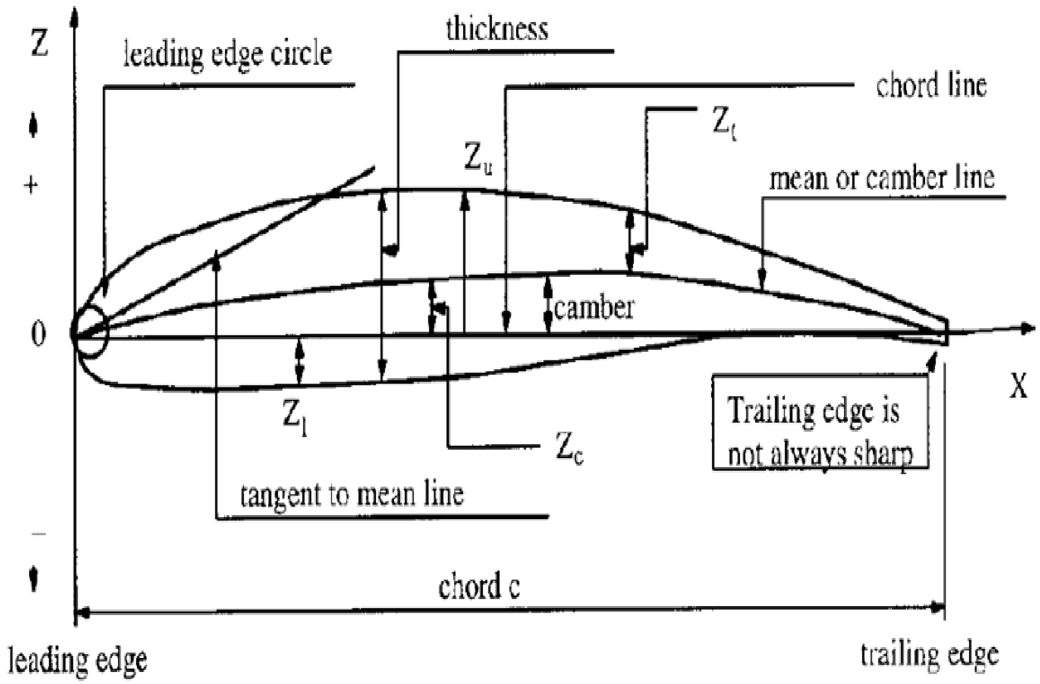
Aerodynamic Sections

(An introduction based on NACA airfoils)

Enrique Ortega
e.ortega@upc.edu

Airfoil geometry

An airfoil can be defined as a 2D wing section which is parallel to the wing symmetry plane or perpendicular to its 1/4th chord line. Most typical airfoil families (like NACA [2]) are constructed by combining a **mean (or camber) line** and a **thickness distribution**.



Extracted from [1].

From the aerodynamic point of view, the main geometric parameters affecting the camber line and thickness distribution are:

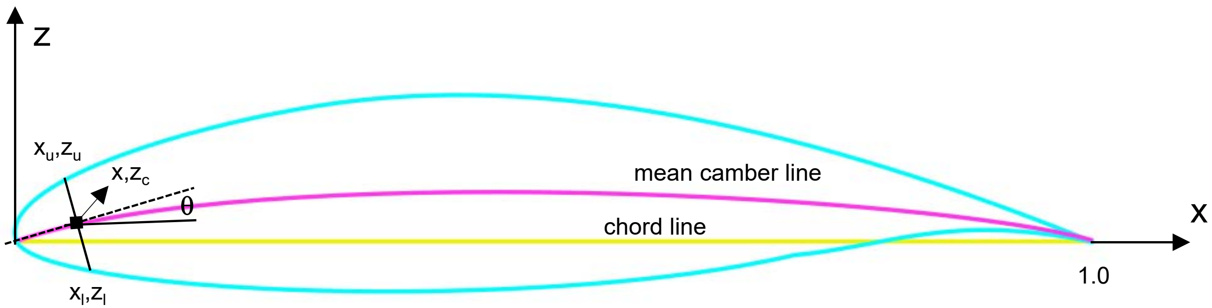
- maximum thickness (and position)
- maximum camber (and position)
- LE radius
- TE angle

Overview of NACA airfoils

- The development of NACA airfoils started around 1930 with a series of systematic studies intended to determine the effects of geometrical parameters on the aerodynamic performance (e.g. NACA R460 (1935)).
- These investigations allowed the development of a methodology to construct airfoils that satisfy specific requirements by combining proper camber lines $z_c(x)$ and thickness distributions $z_t(x)$.

For example, a NACA airfoil is constructed by

$$\begin{cases} x_u = x - z_t(x)\sin\theta \\ z_u = z_c(x) + z_t(x)\cos\theta \end{cases} \quad \begin{cases} x_l = x + z_t(x)\sin\theta \\ z_l = z_c(x) - z_t(x)\cos\theta \end{cases} \qquad (1)$$



with $\theta = \tan^{-1}\left(\frac{dz_c}{dx}\right)$ (2)

where $z_c(x)$ and $z_t(x)$ are designed to obtain a desired performance (the more advanced NACA airfoils also include some additional design variables). This method gave origin to different families of airfoils with particular characteristics.

NACA 4-digit series

- The 4-digit series is the first family of airfoils developed by NACA.
- The thickness distribution $y_t(x)$ is based on Clark Y (U.S navy) and Gottingen 398 airfoils. The maximum thickness (t) is located at 30% of the chord.
- The camber line $y_c(x)$ is constructed by combining two quadratic curves that merges at the position of the maximum camber (p), which is usually denoted by f.
- The leading edge radius (r_{le}) and trailing edge angle (δ_{te}) are both a function of the thickness distribution.
- NACA 4-digits airfoils have good stall characteristics and high-speed performance (x_{cp} movement). However, the maximum lift is relatively low and the pitching moment and drag are elevated.

Numbering system: NACA - X X X X

thickness (t) in percent of chord

maximum camber position (p) in tenths of chord

maximum camber (f) in percent of chord

Geometrical definition for the NACA 4-digit airfoils

The camber line and thickness distributions are given by [2]

$$y_t = \pm\frac{t}{0.2}\left(0.2969\sqrt{x} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1015x^4\right) \quad (3)$$

$$\begin{aligned} y_c &= \frac{f}{p^2}\left(2px - x^2\right) && 0 \le x \le p \\ y_c &= \frac{f}{\left(1-p\right)^2}\left(1 - 2p + 2px - x^2\right) && p \le x \le 1 \end{aligned} \quad (4)$$

$$r_{le} = 1.1019t^2 \qquad \delta_{TE} = 2\tan^{-1}\left(1.16925t\right) \quad (5)$$

where *t* and *f* are the maximum thickness and camber, respectively, and *p* is the maximum camber position (all these values are given in tenths of chord).

The procedure to construct a NACA airfoil is as follows

1. Define values of x along the airfoil chord (e.g. using uniform or full cosine distribution).
2. For *t*, *f* and *p* given, compute $y_t(x)$ and $y_c(x)$ from Eqs. (3) and (4).
3. Determine the final coordinates of the airfoil from Eqs. (1) and (2).

There is also a modified NACA 4-digit series with variable maximum thickness position and LE radius. These airfoils are designated by NACA XXXX-IT, where I denotes the r_{le} and T the maximum thickness position (both in tenths of the chord).

NACA 5-digit series

- These airfoils adopt the thickness distribution of the 4-digit series.
- The camber line is designed shifting the maximum camber position towards the leading edge. This increases the lift and keeps the **pitching moment low**.
- There is also reflex camber lines to achieve near zero pitching moment.
- In these airfoils, a design C_l is specified in order to determine the camber.
- These airfoils have poor stall behavior and a relatively high drag.

Numbering system: NACA - X X X X X

maximum thickness (t) in percent of the chord

0 means standard mean line, 1 is reflex

two times the maximum camber position (p) in percent of chord

3/20 of the design C_l of the camber line (proportional to f)

NACA 5-digit mean lines

As mentioned before, the thickness distribution is similar to that of the 4-digit family. The camber line is given by [2]

$$y_c = \frac{1}{6}k_1\left[x^3 - 3mx^2 + m^2(3-m)x\right] \quad 0 \le x \le m$$
$$y_c = \frac{1}{6}k_1\, m^3\left(1-x\right) \qquad m \le x \le 1 \tag{6}$$

mean line	position of maximum camber	merging position m	Value of k_1 @ Cl_i = 0.3
210	0.05	0.0580	361.4
220	0.10	0.1260	51.640
230	0.15	0.2025	15.957
240	0.20	0.2900	6.643
250	0.25	0.3910	3.23

Note that for other values of Cli, k_1 is obtained proportionally, i.e. $k_1/0.3\cdot Cli$

The procedure to construct a NACA 5-digit airfoil is similar to that presented before for the 4-digit series.

NACA 6-digit series

- These airfoils are the most widely used NACA airfoils.
- The design of the 6-digit family, which follows only aerodynamic criteria, was intended to achieve constant load over the upper surface of the airfoil (reducing adverse pressure gradient).
- The low Cp gradient over the upper surface allows increasing the **extension of laminar flow**, thus reducing the drag. The drag curve is characterized by the presence of the so-called laminar bucket (low and relatively constant drag over a given range of C_l).
- The 6-digit airfoils have high Cl_{max} and moderate x_{cp} displacement at high speeds. On the other side, the stall behavior is poor and the drag is relatively high outside the design range. The pitching moment is also relatively high.
- The thickness and camber distribution for these airfoils are given (mostly) in tabulated form. Some analytical expressions are also available (but they are not as simple as the previous ones).

Numbering system: NACA – X X X X X X a = x

indicates the type of camber line. The value gives the extent of uniform load along the chord (in tenths). 1 is assumed if not specified

thickness (t) in percent of the chord

design C_l in tenths

range of C_l (in tenths) about Cl_i for which favorable Cp gradients exist on both surfaces

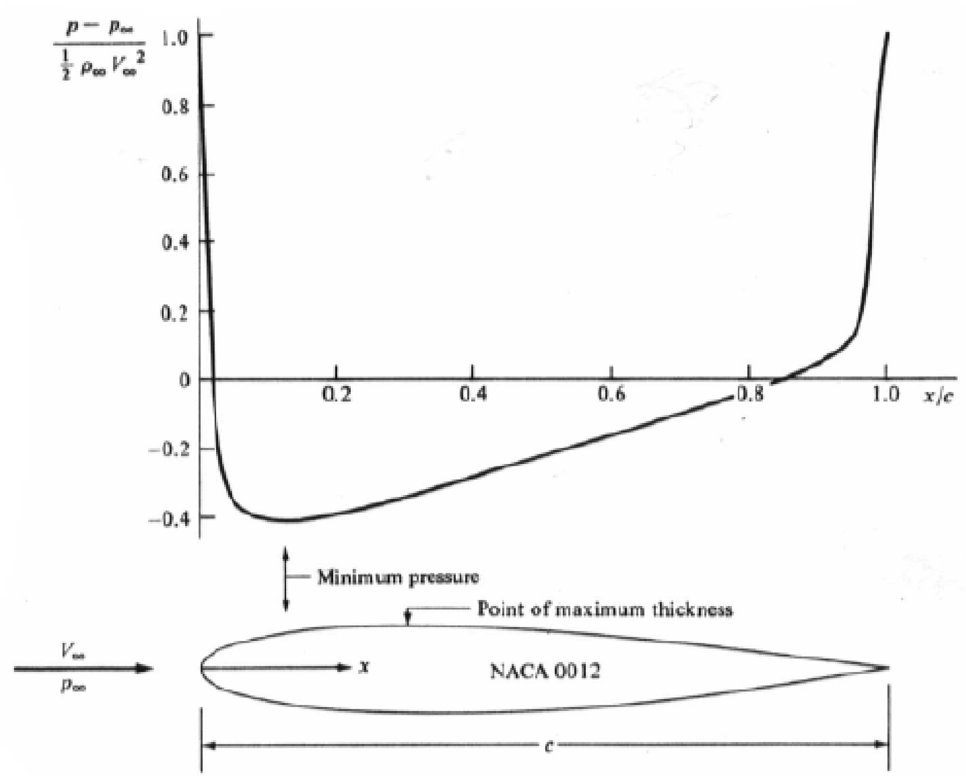
position of Cp_{min} in tenths of the chord obtained for the basic symmetrical thickness distribution at C_l = 0

indicates the series designation

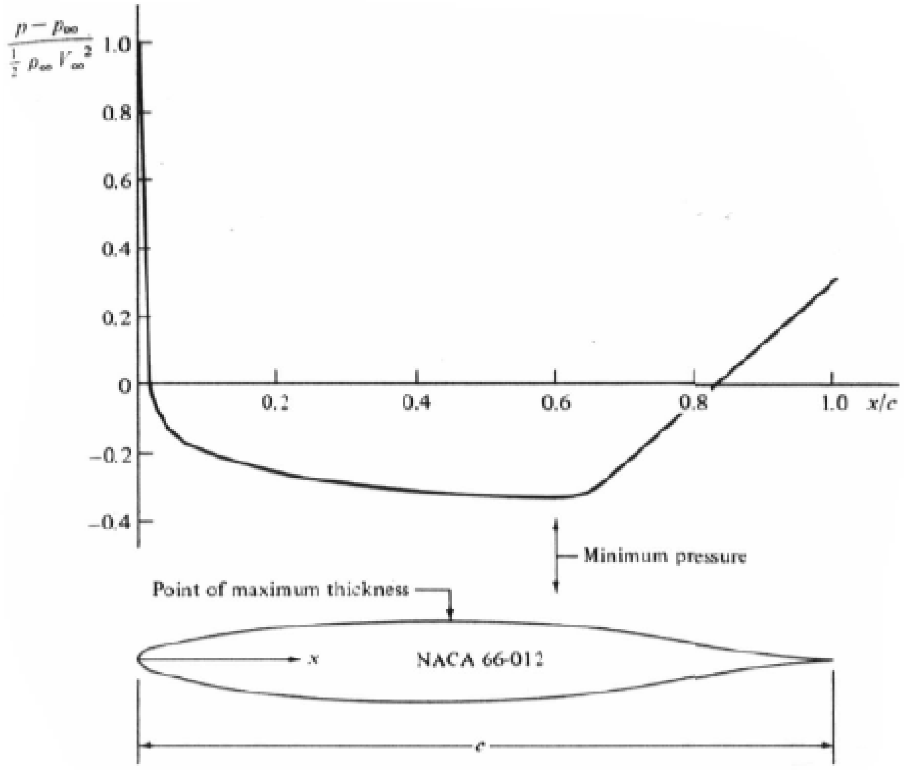
Example: NACA 64_1-212, a=0.6

The 1st digit indicates the airfoil series. The 2nd digit says that the minimum pressure is located at 0.4c (for the basic symmetric thickness distribution at zero lift). The subscript “1” and the 4th digit indicate that the minimum drag is obtained for a range of ΔCl=0.1 about Cl_i = 0.2, i.e. Cl = 0.2$\pm$0.1. The final two digits give the maximum thickness, which is 12% of chord. The indication *a = 0.6* refers to the type of camber line. In this case, the load is uniform up to 0.6c (then it decreases linearly towards the TE).

Effects of thickness distribution on Cp



Standard airfoil



Laminar flow airfoil

NACA 7-digit series

- These airfoils are an evolution of the 6-digit series, and are intended to maximize the laminar flow extension (particularly on the lower side of the airfoil).
- NACA-7 series have reduced drag (in comparison with the series 6) and low pitching moment with a considerable high design C_l.

Numbering system: NACA – X X X X X X X

the last three digits are similar as in the series 6

this letter indicates airfoils with similar parameters

position of Cp_{min} on the lower surface (in tenths of the chord)

position of Cp_{min} on the upper surface (in tenths of the chord)

indicates the series designation

NACA 8-digit series

- These sections are based on NACA 6 and 7 series and inherit their main features.
- The 8-digit airfoils are intended for high-speed flows (transonic and supersonic).

1. Roskam, J., Lan C. Airplane aerodynamics and performance. Kansas: DAR Corporation (1997).
2. Abbott, I. H., von Doenhoff, A. E., & Stivers, L. Report No. 824–Summary of Airfoil Data. *National Advisory Committee for Aeronautics* (1945).
3. Abbott, I. H., Doenhoff, A. E. V. Theory of wing sections. Including a summary of airfoil data. New York: Dover (1959).

Additional information on wing sections:

4-digit series: NACA R 460 (1933) and 492 (1934)

5-digit series: NACA R 537 (1935) and 610 (1937)

6-digit series: NACA R 824 (1945), 903 (1948) and NASA R-84 (1958)

Supercritical sections (increased M_{crit} and delayed drag rise): NASA TM X-1109 (1965)

General aviation airfoils (GA(W)): NASA TN-D 7428 (1973)

Low Reynolds airfoils: Althaus, Dieter. *Profilpolaren für den Modellflug.* Neckar-Verlag, 1980.

see also *http://aerospace.illinois.edu/m-selig/uiuc_lsat.html*

Other general information: *http://aerospace.illinois.edu/m-selig/ads/coord_database.html*

http://www.pdas.com/naca456.html

Enrique Ortega
e.ortega@upc.edu