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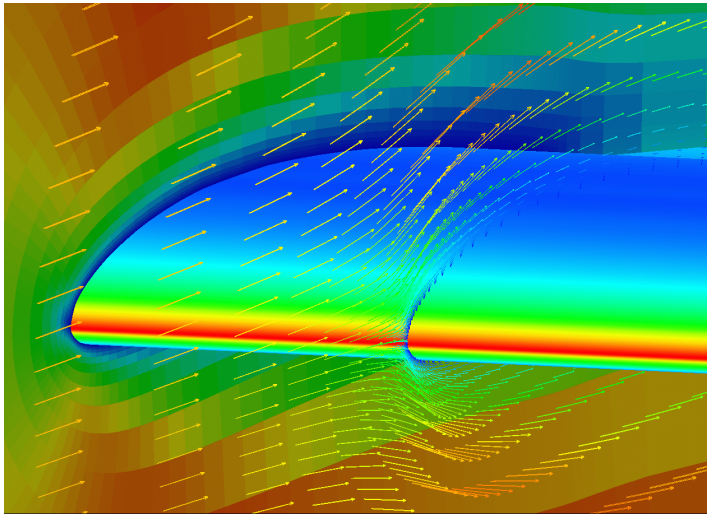
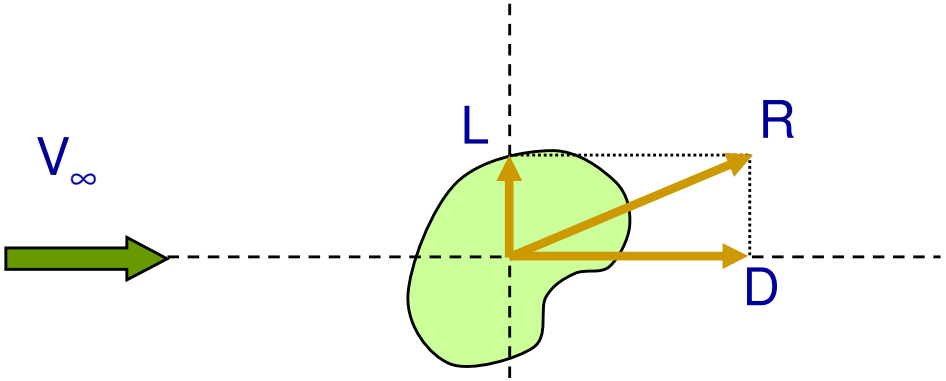


Energías Renovables

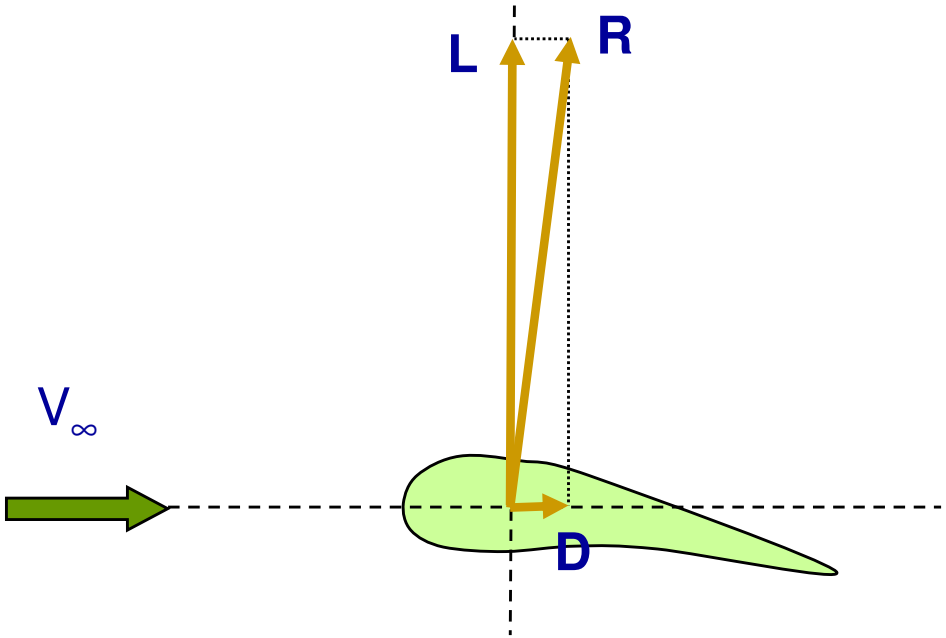
Perfiles aerodinámicos

Fuerzas sobre superficies



Fuerzas sobre cuerpo romo:

- $D \geq L$
- $D \uparrow\uparrow$



Fuerzas sobre superficie sustentadora:

- $L >> D$ en condiciones diseño
- $D \downarrow\downarrow$

- Perfil avión/ Gran aerogenerador:
  $L/D \geq 120$
- Aerogenerador pequeño autónomo:
  $L/D \approx 30$
- Aerobomba pistón:
  $L/D \approx 10$

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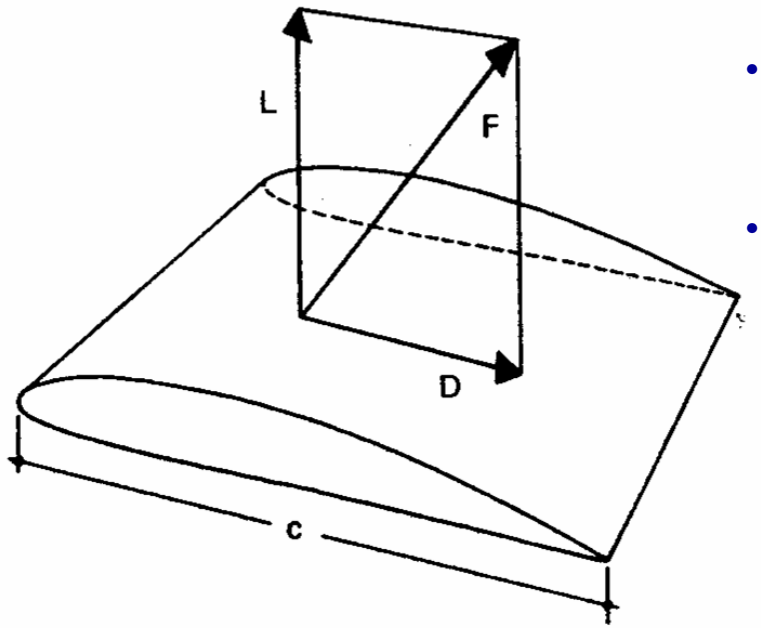
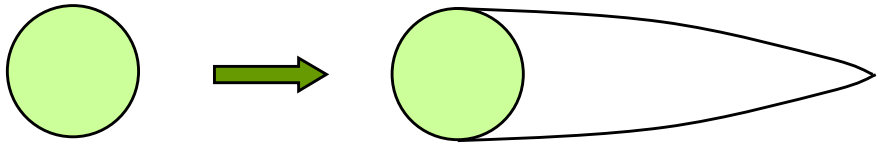
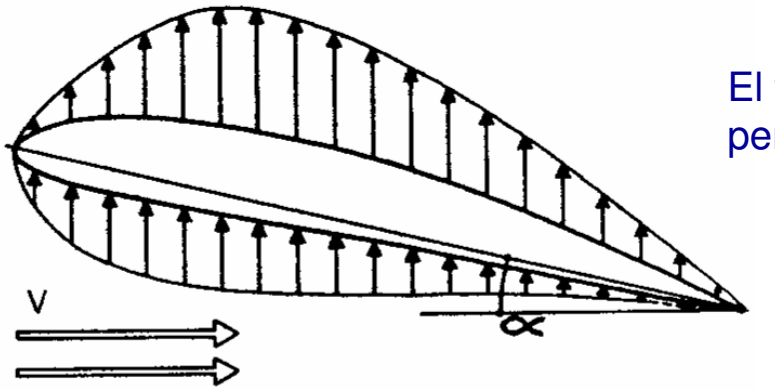
Sustentación



- Distribución de presiones como principal contribución a gran sustentación (L/D >>1).
- Necesidad introducir asimetrías entre parte superior e inferior
  - Curvatura
  - Ángulo Ataque.
- Necesidad de mantener el flujo adherido a superficie
  - Necesidad fuselar para reducir gradientes adversos





El fuselado además reduce mucho D al evitar el desprendimiento, permitiendo alcanzar L/D >> 1.

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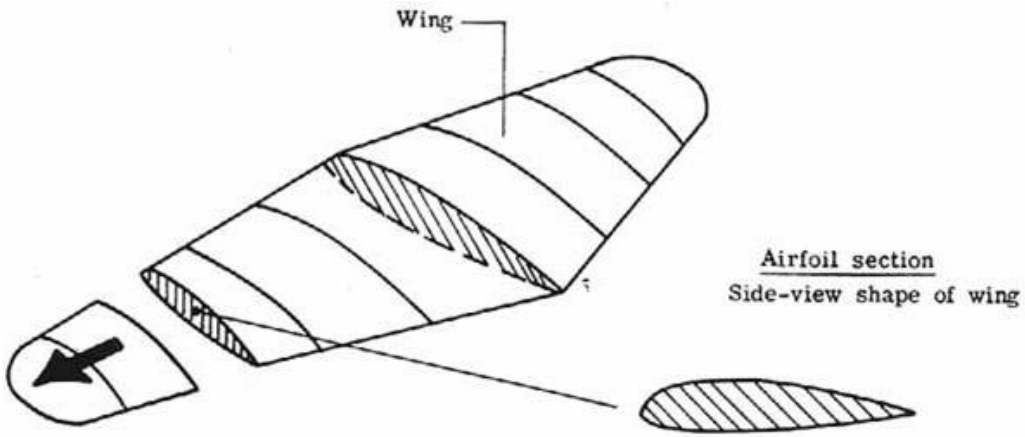
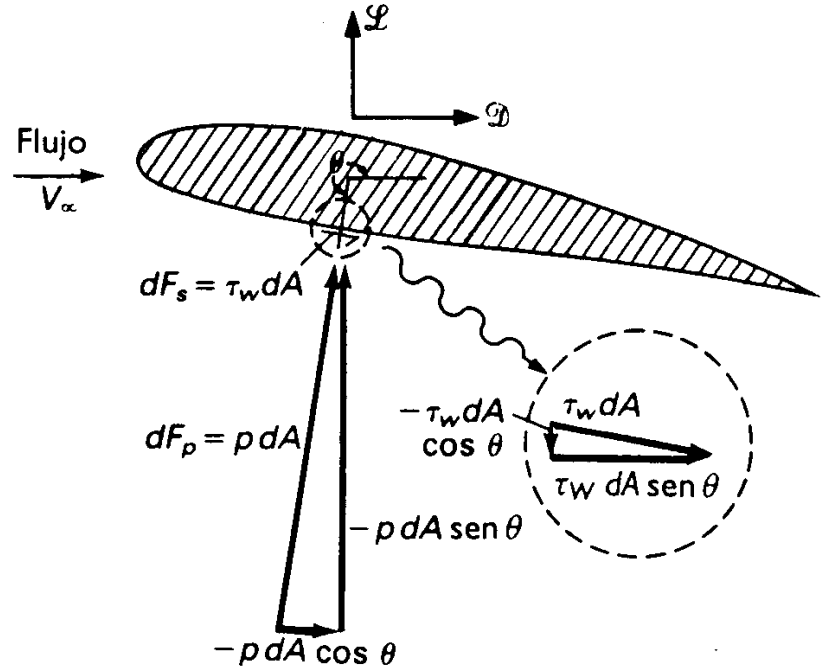
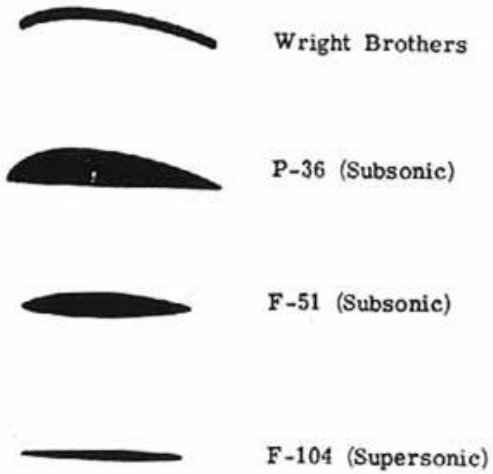
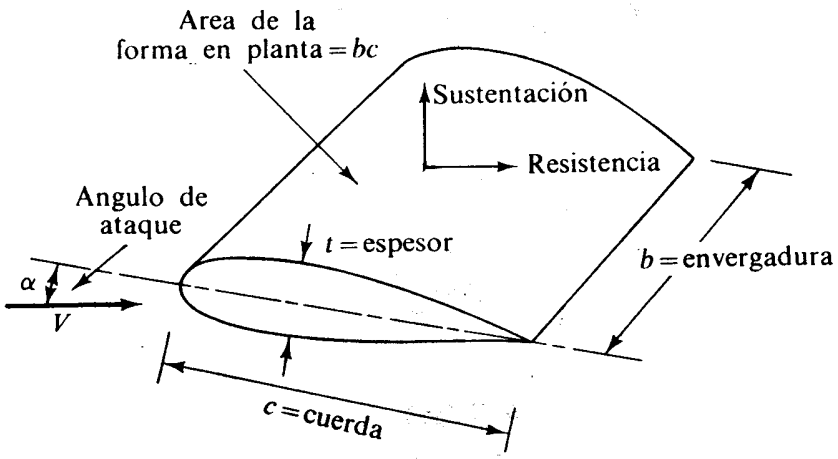
Superficies sustentadoras

La superficie sustentadora compuesta de perfiles bidimensionales









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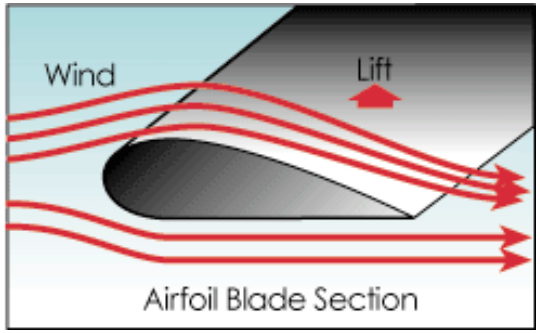
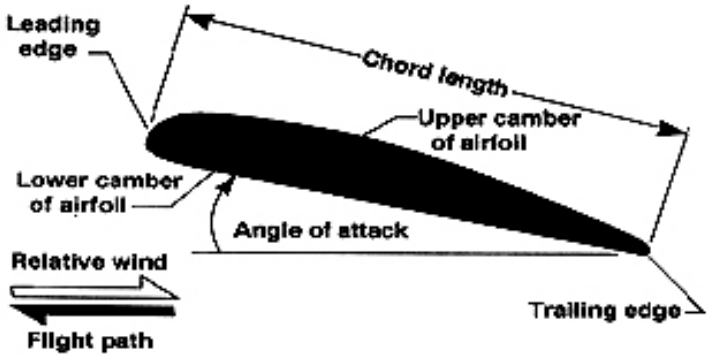
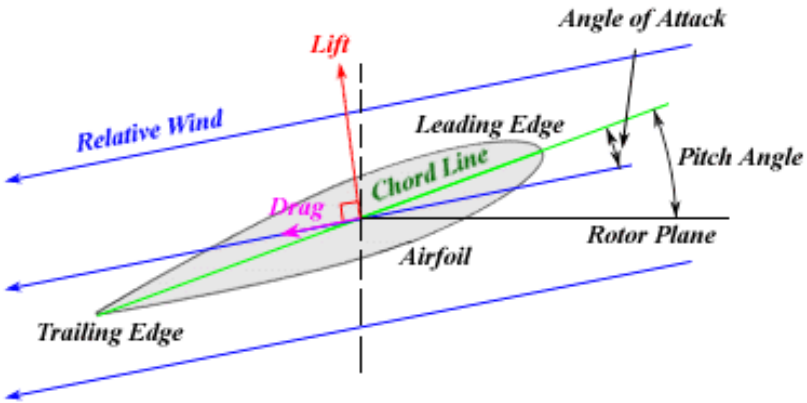
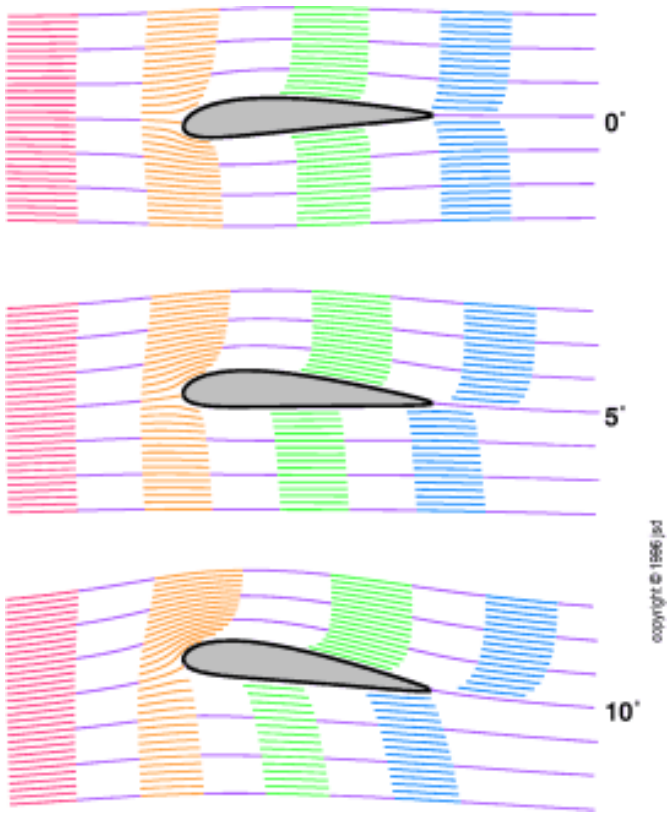
Superficies sustentadoras









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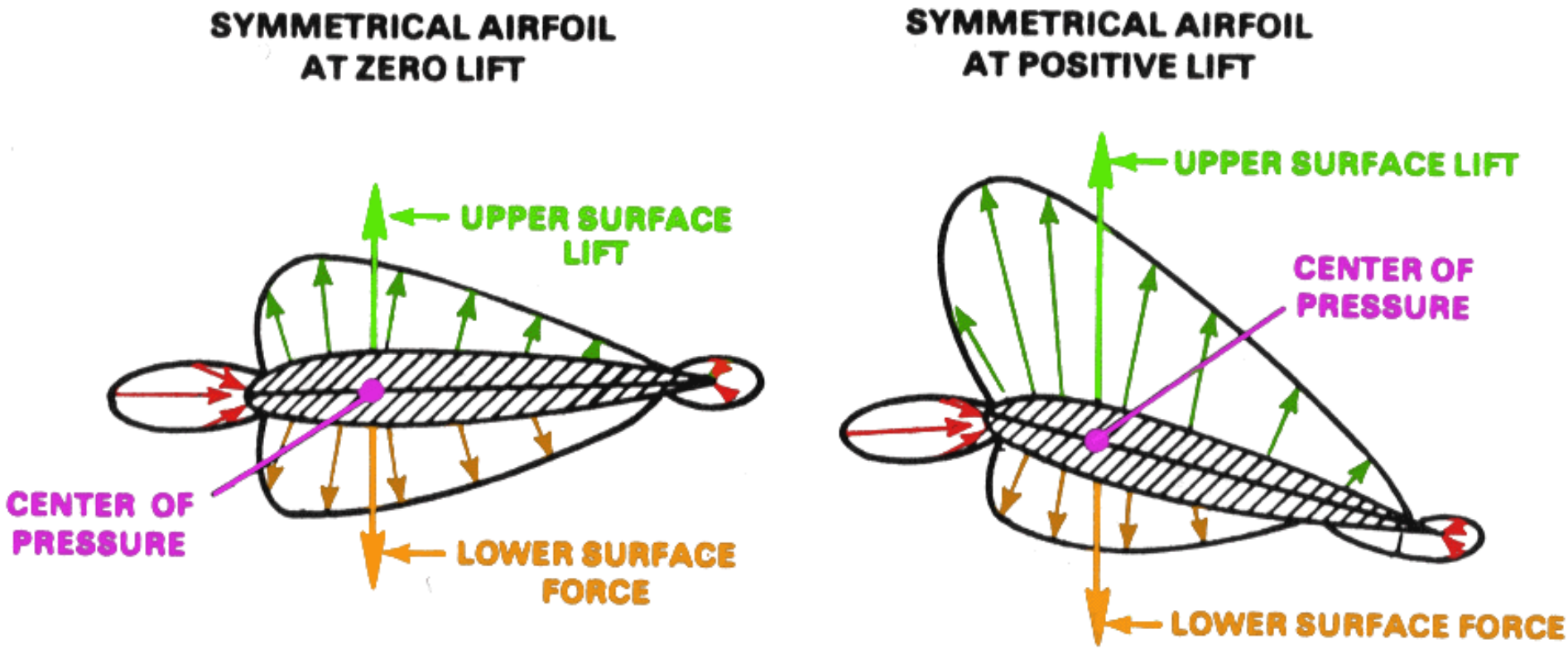
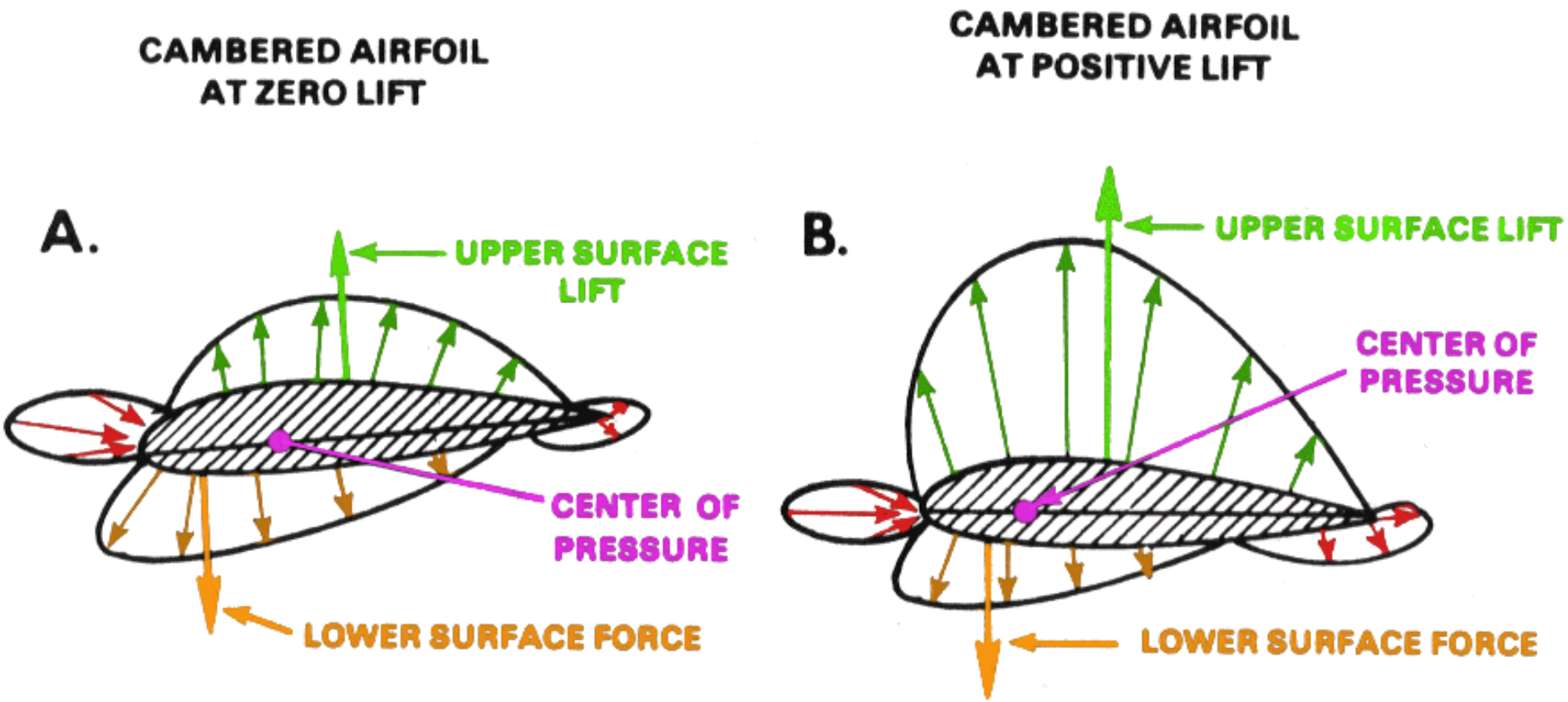
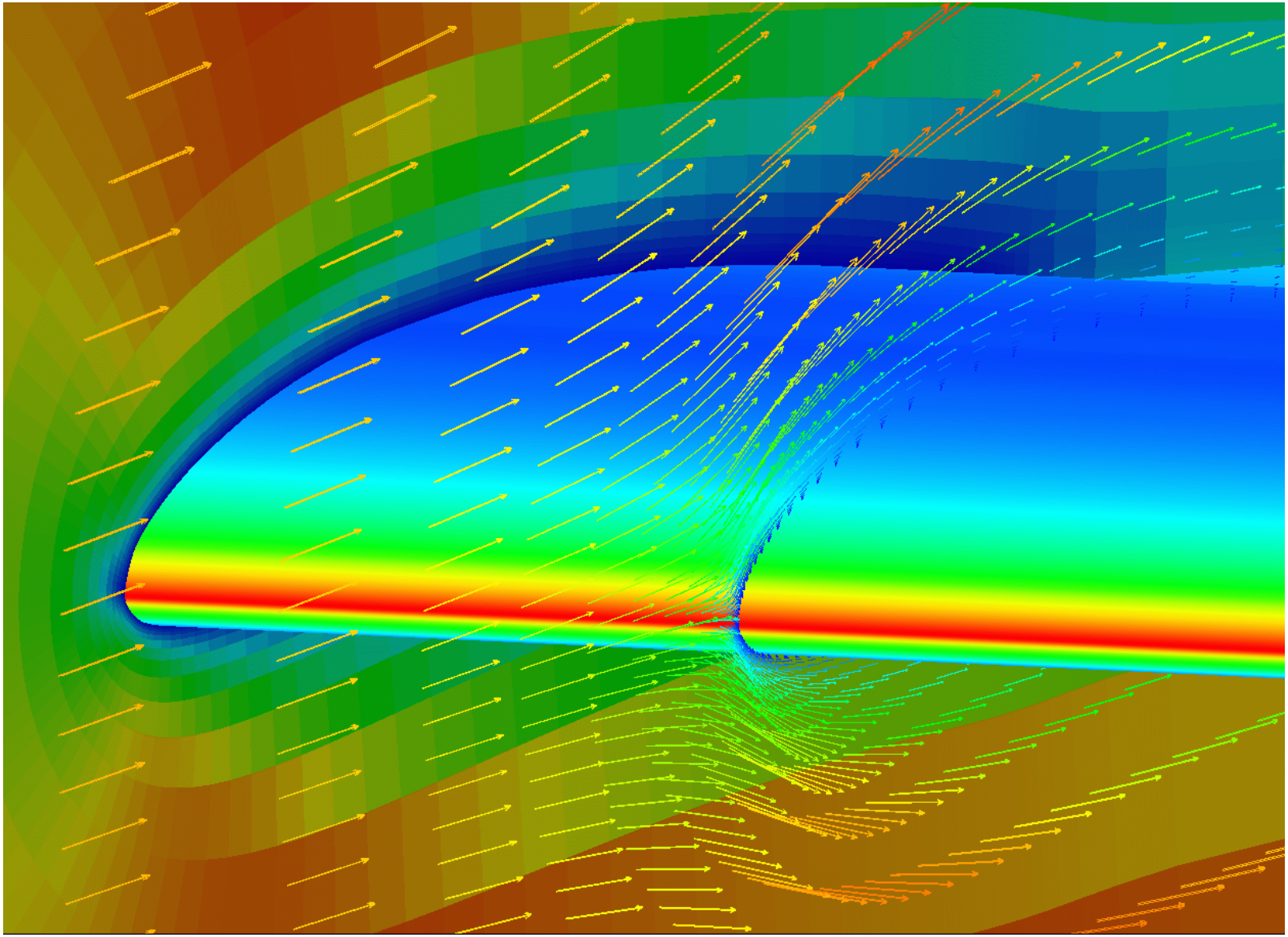
Superficies sustentadoras



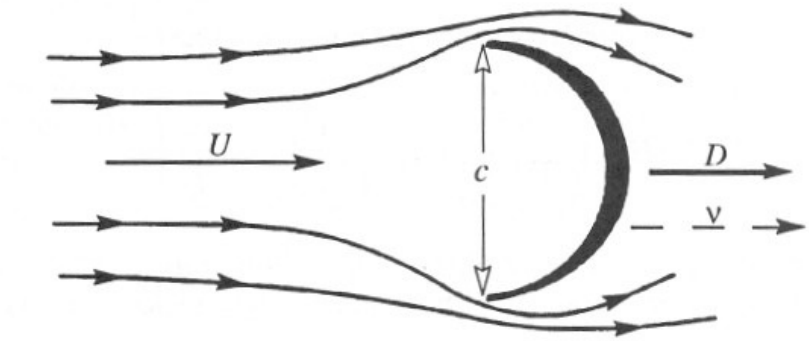
Superficies sustentadoras

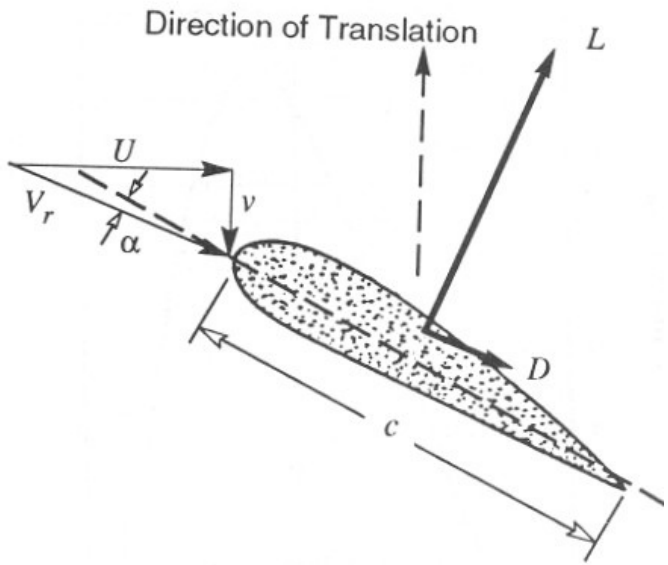


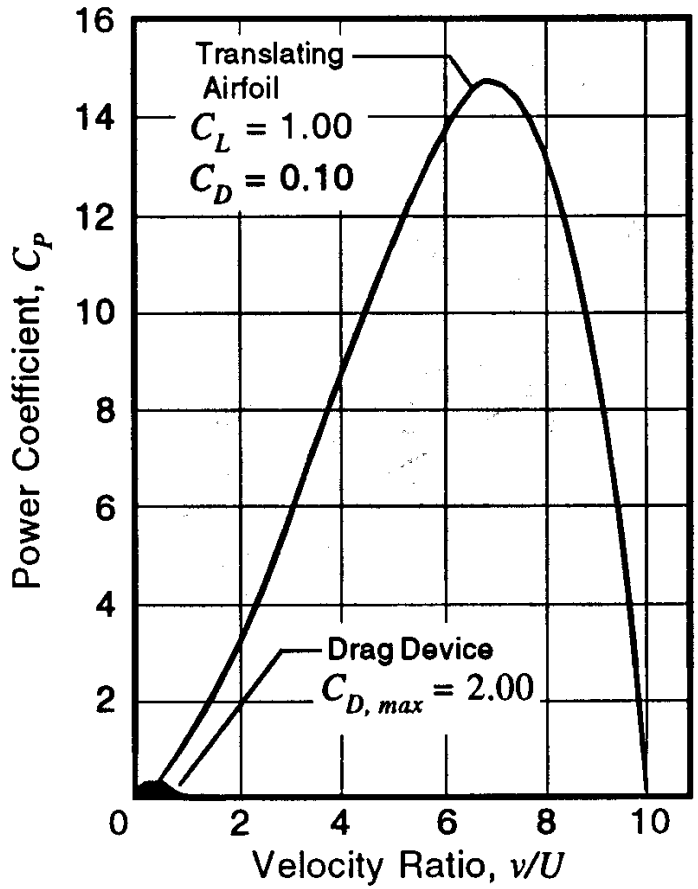
Superficies sustentadoras



Superficies sustentadoras

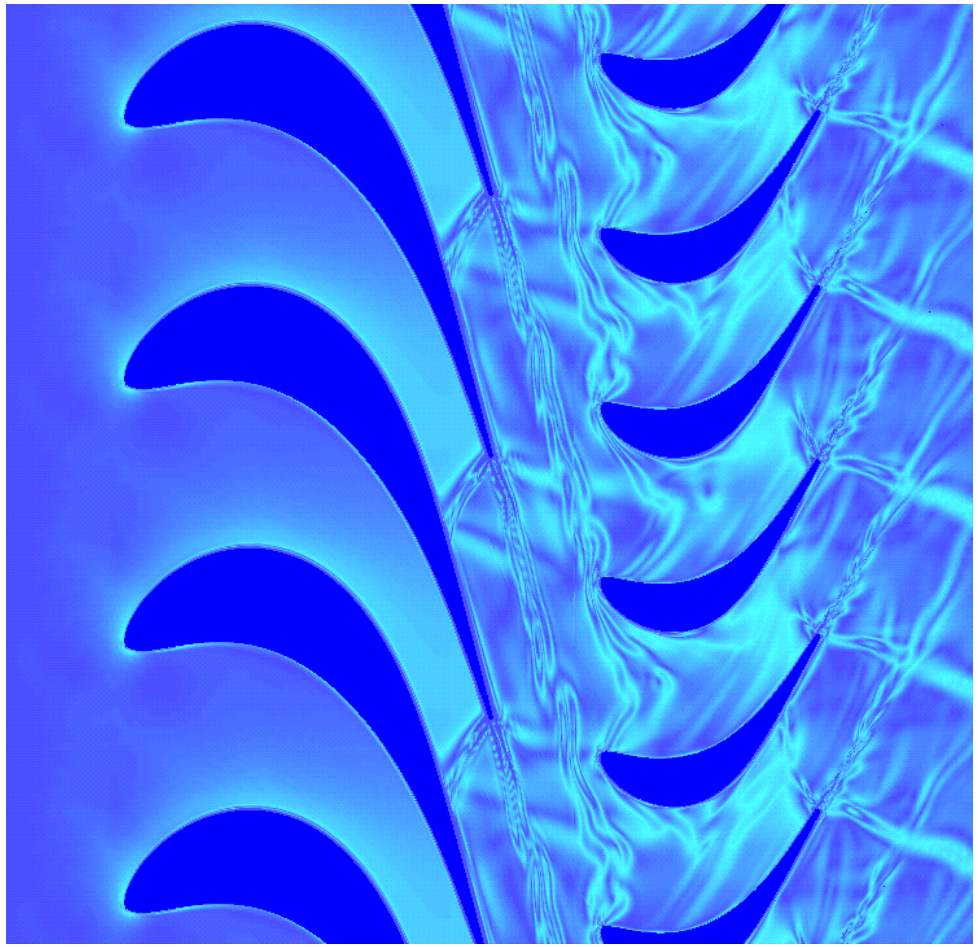






Además, el uso de superficies sustentadoras reduce el tamaño y déficit energético de las estelas, reduciendo pérdidas en un parque eólico

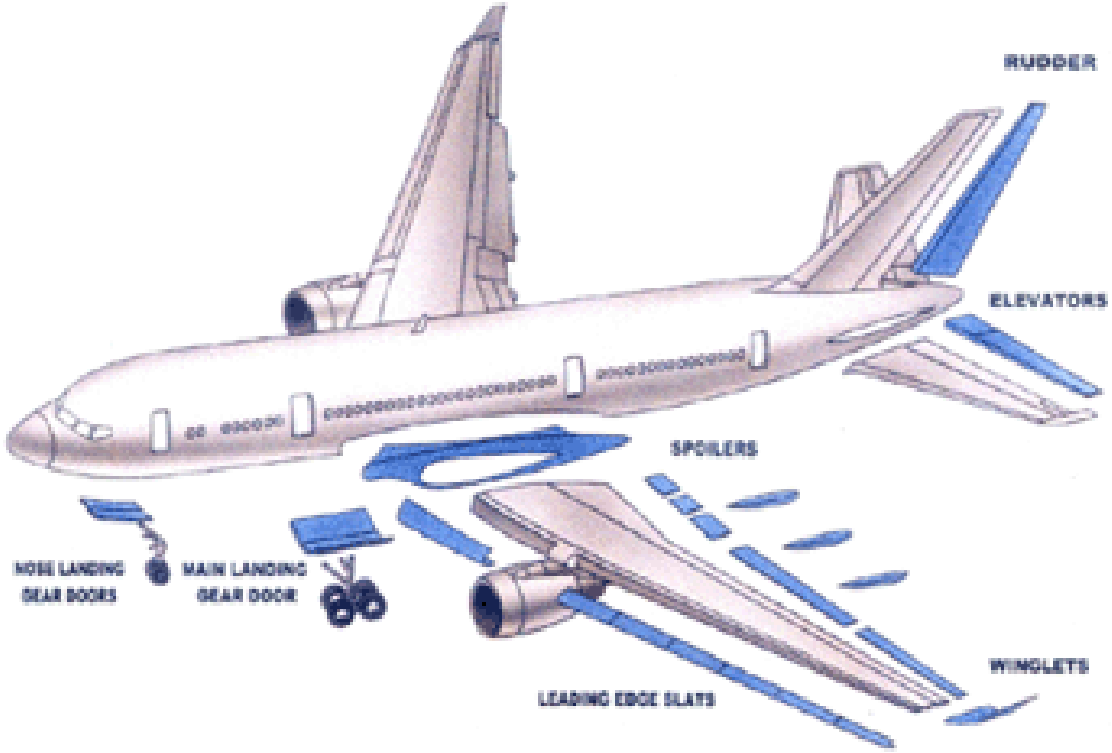
Superficies sustentadoras



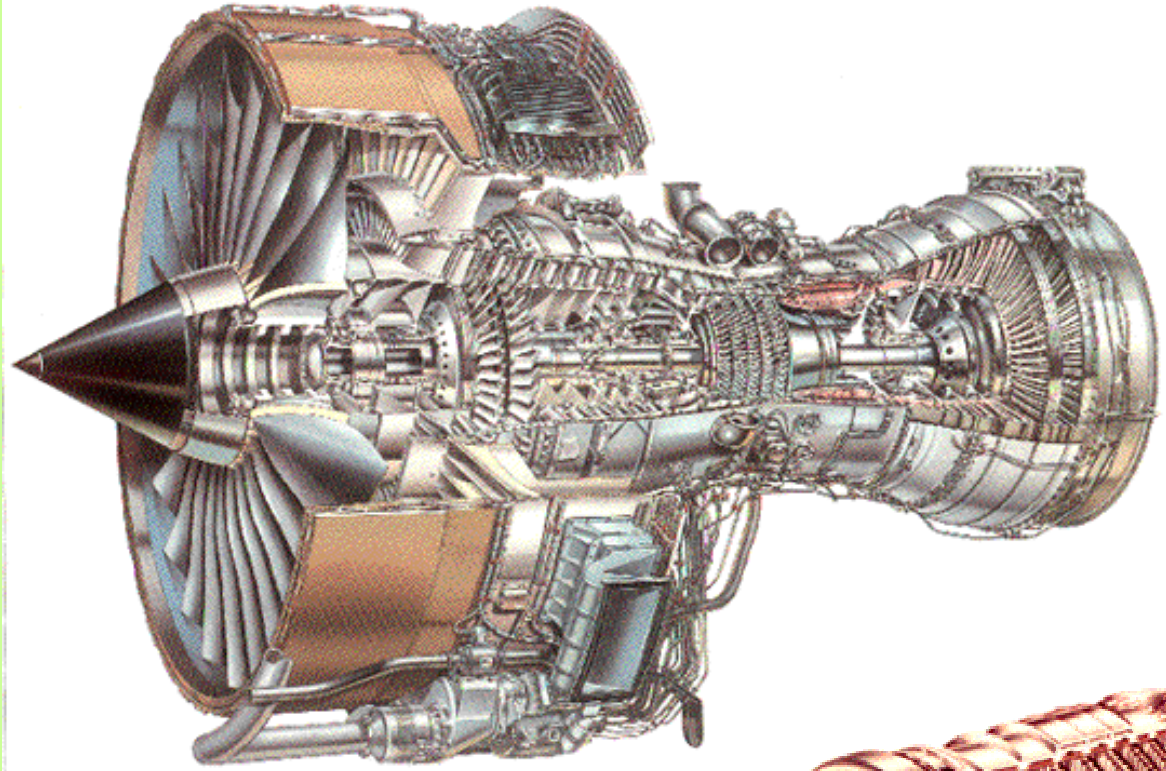
- Desarrollo superficies sustentadores eficientes

- Gran cantidad aplicaciones técnicas que han visto la luz o aumentado su eficiencia:
  - Aviones
  - Helicópteros
  - Turboreactores
  - Turbocompresores
  - Turboacoplamientos
  - Turbinas de vapor
  - Turbinas de gas
  - Turbinas hidráulicas
  - Aerogeneradores

Aplicaciones superficies sustentadoras

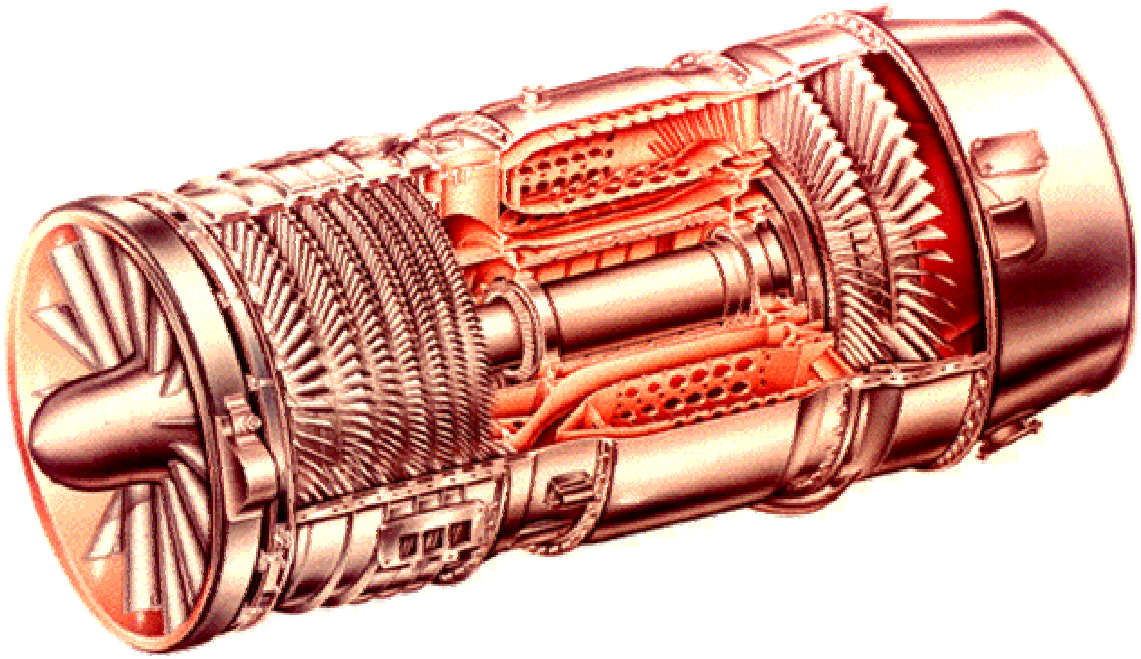


Aplicaciones superficies sustentadoras



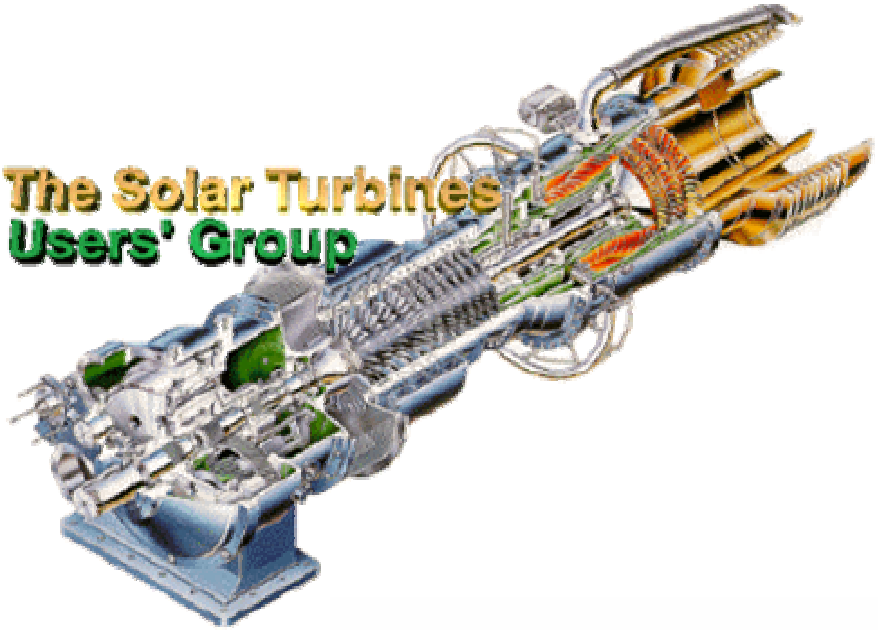
RR Trent

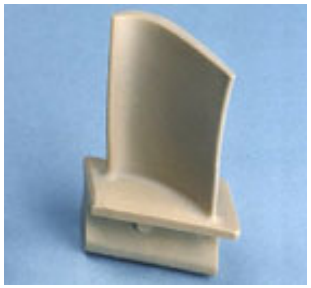
J85

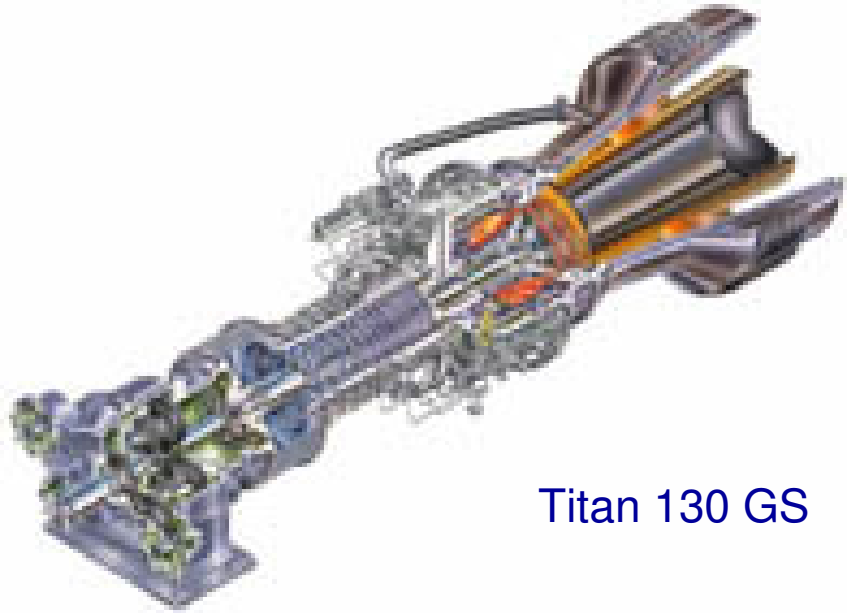


Aplicaciones superficies sustentadoras

Aplicaciones superficies sustentadoras







Titan 130 GS

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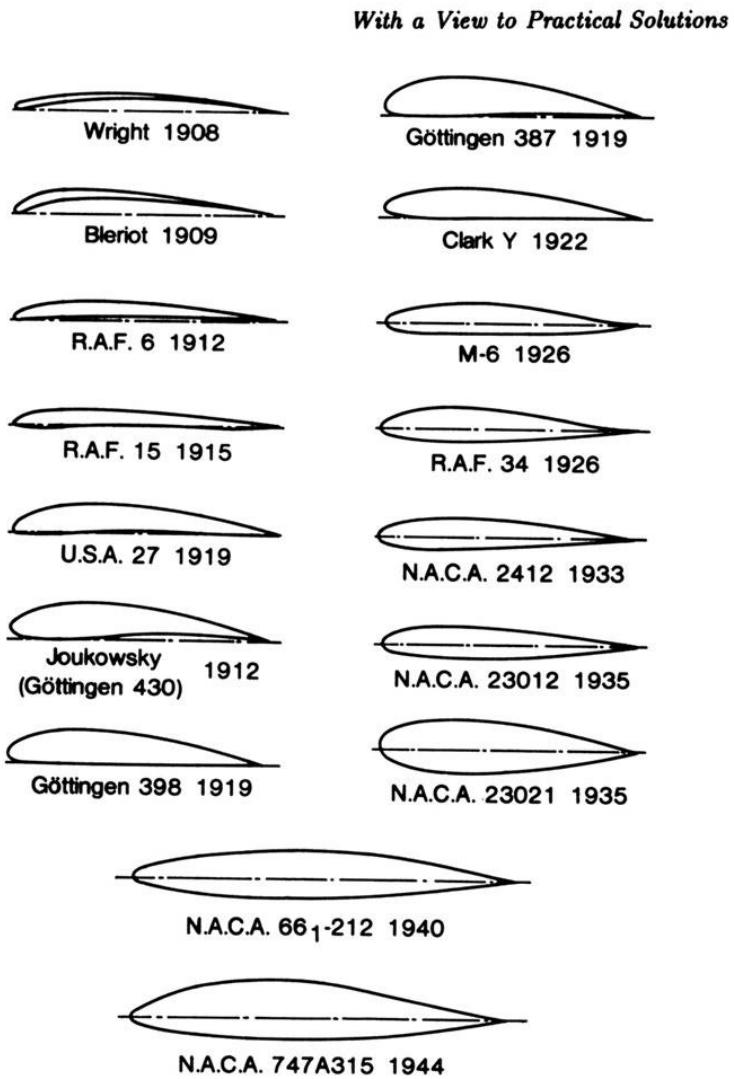
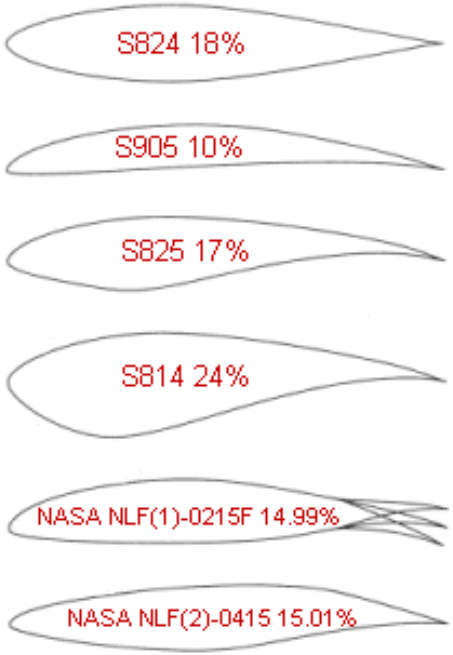
Aplicaciones superficies sustentadoras

Geometría superficies sustentadoras



The historical evolution of airfoil sections, 1908–1944. The last two shapes (N.A.C.A. 66$_1$-212 and N.A.C.A. 747A315) are low-drag sections designed to have laminar flow over 60 to 70 percent of chord on both the upper and the lower surface. Note that the laminar flow sections are thickest near the center of their chords.



NACA (National Advisory Comittee for Aeronautics)

NACA xyzz

- x = curvatura máxima (% de c)
- y = localización curvatura máxima (10 x % de c)
- zz = espesor / cuerda (%)
- espesor máximo a 30% de la cuerda

NACA xyyzz

- x = C_L / 0,15
- yy = localización curvatura máxima (% de c)
- zz = espesor / cuerda (%)
- espesor máximo a 30% de la cuerda

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Caracterización superficies sustentadoras

- Coeficiente sustentación:

$$c_L = \frac{L}{\frac{1}{2} \cdot \rho \cdot V_r^2 \cdot c}$$

- Coeficiente resistencia:

$$c_D = \frac{D}{\frac{1}{2} \cdot \rho \cdot V_r^2 \cdot c}$$

- Eficiencia aerodinámica: c_L/c_D

$$c_L = f\left(\frac{\mu}{\rho V_r c}, \alpha, \frac{k}{c}, \text{forma}\right)$$

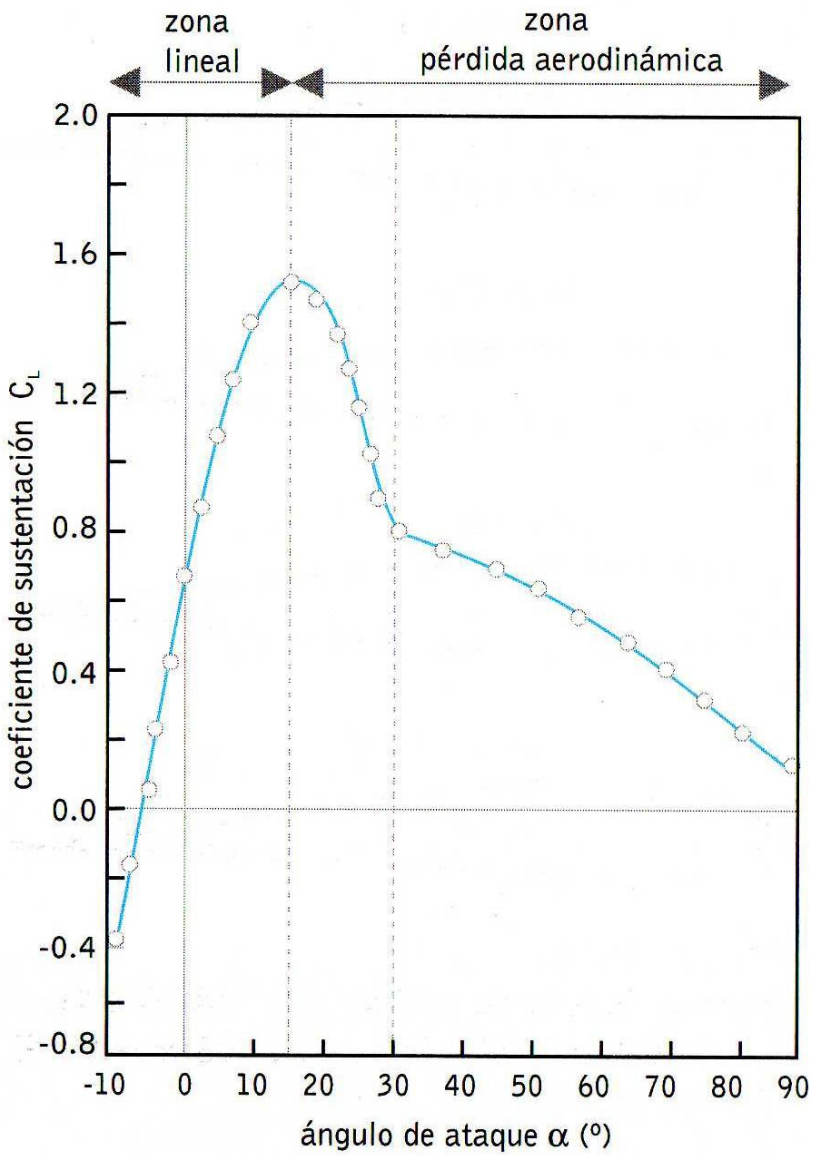
$$c_D = f\left(\frac{\mu}{\rho V_r c}, \alpha, \frac{k}{c}, \text{forma}\right)$$

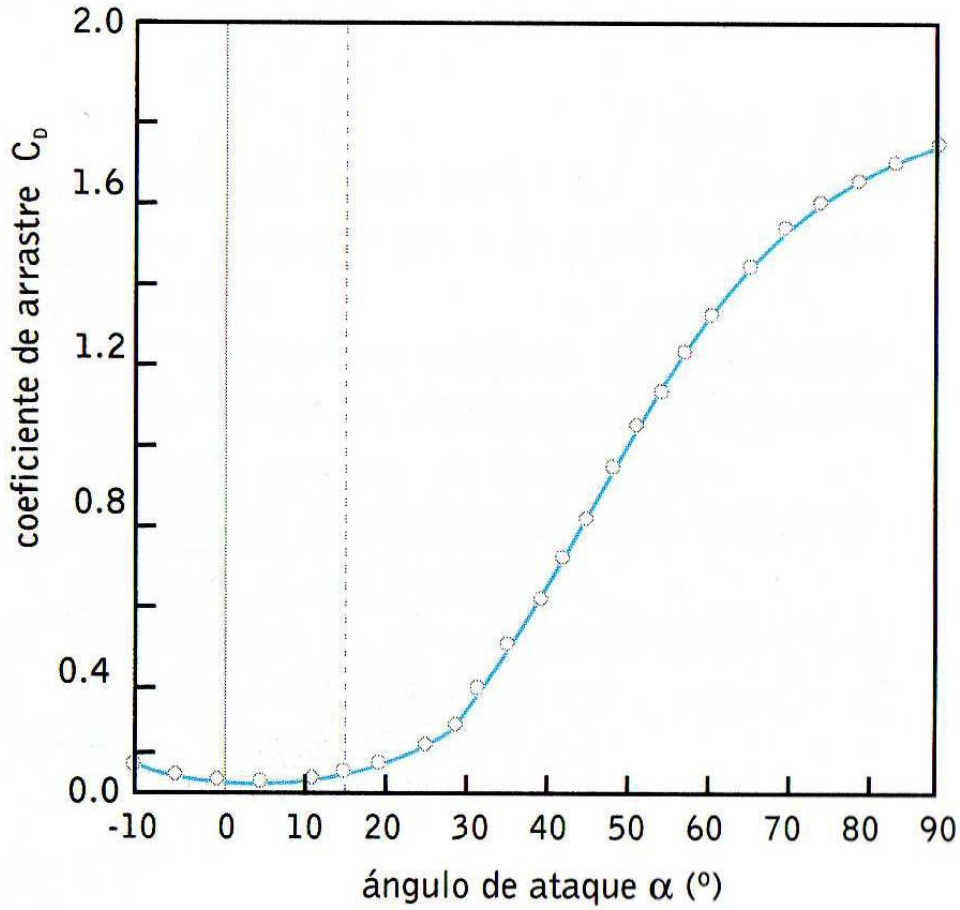
$$c_L \approx f(\alpha, \text{forma})$$

$$c_D = f(\alpha, \text{forma})$$

Caracterización superficies sustentadoras

En aplicaciones convencionales se emplean con $\alpha < \alpha_{pérdida}$





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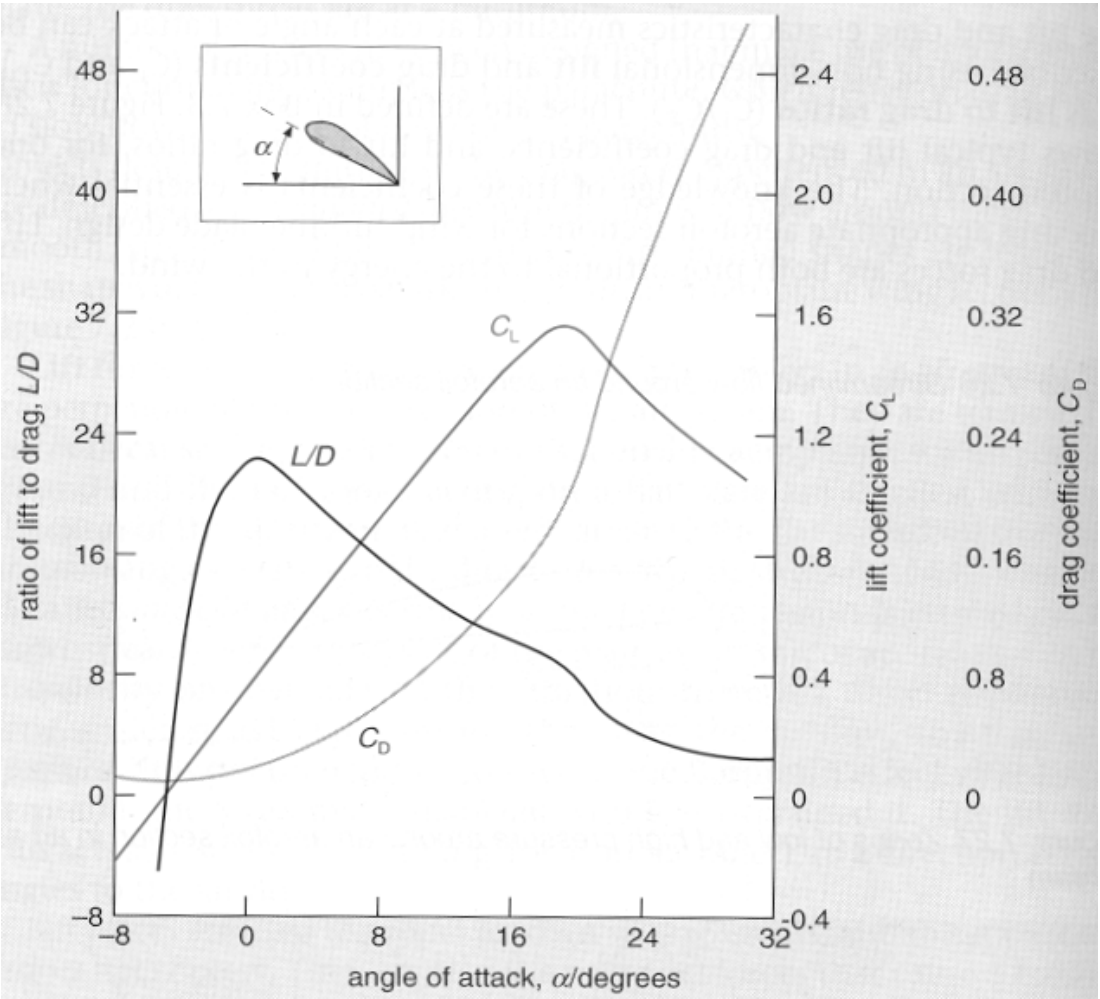
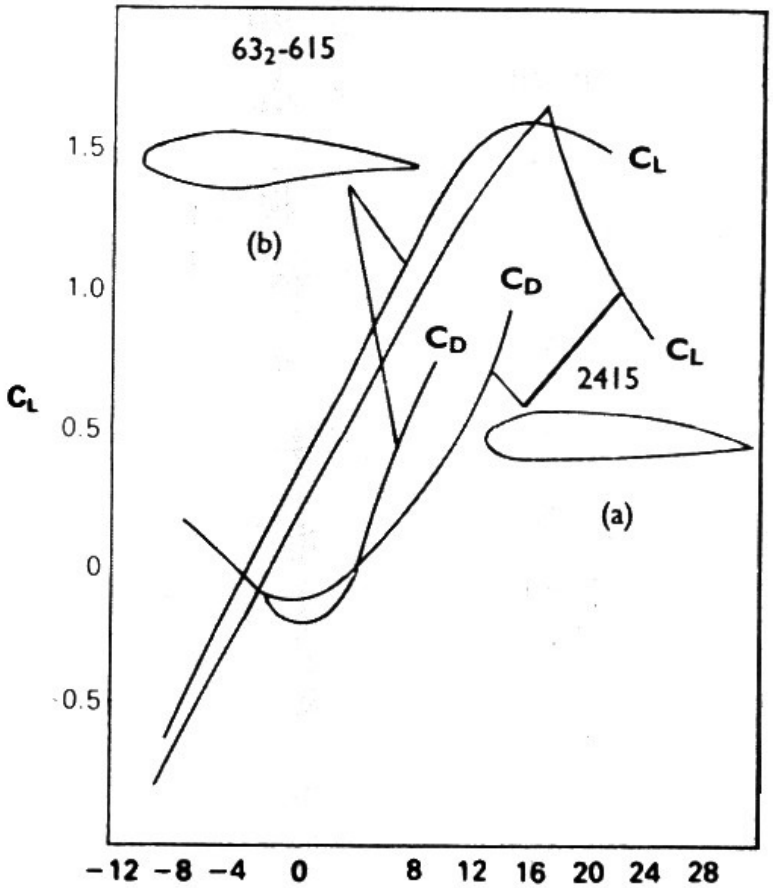
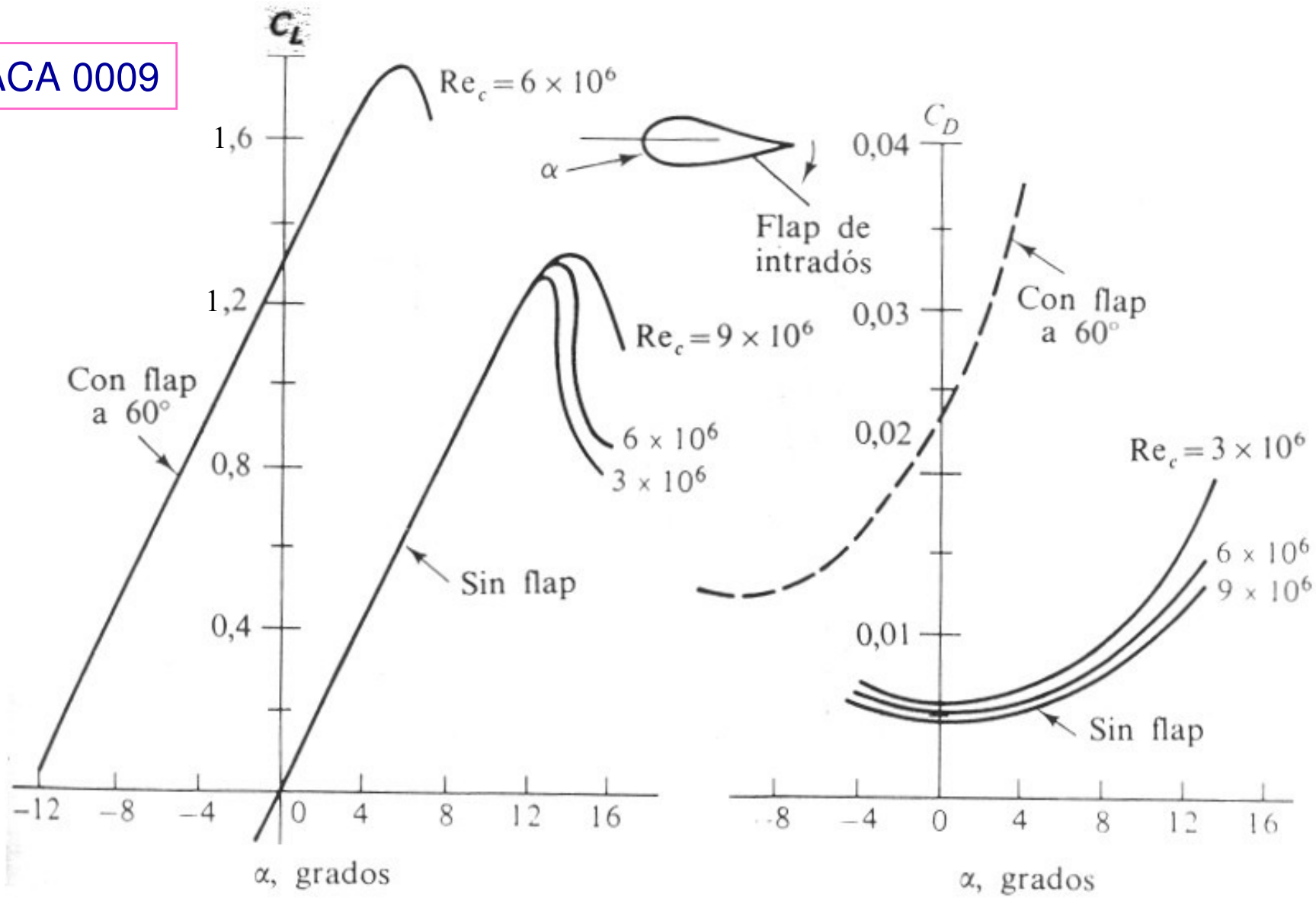
Caracterización superficies sustentadoras





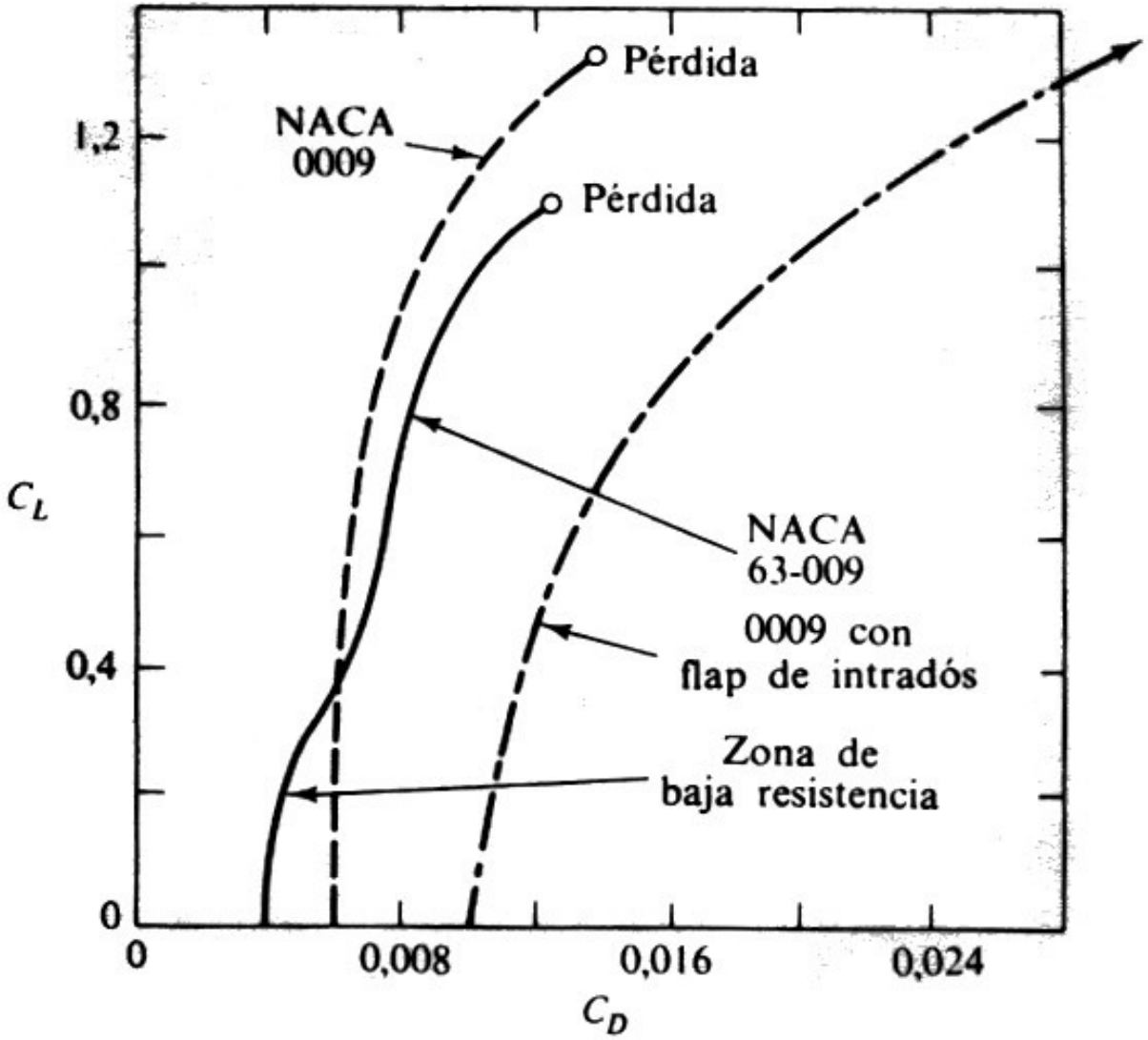
Caracterización superficies sustentadoras

NACA 0009



Caracterización superficies sustentadoras

Perfil Laminar



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Caracterización superficies sustentadoras

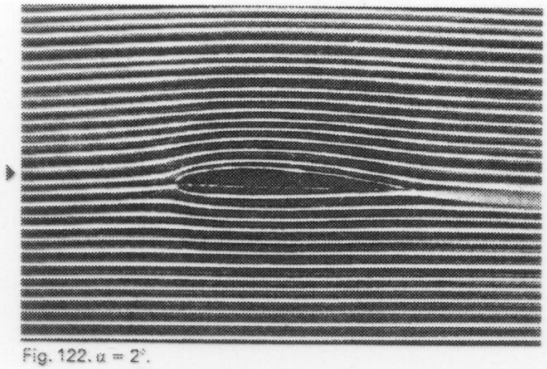


Fig. 122. $\alpha = 2°$.

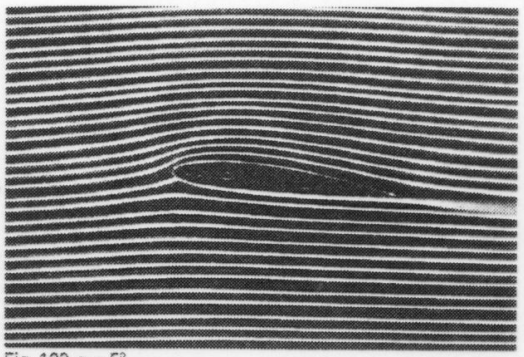


Fig. 123. $\alpha = 5°$.

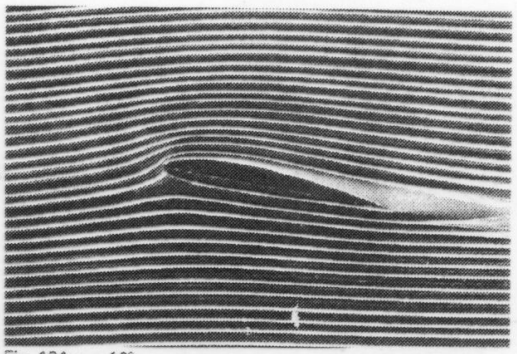


Fig. 124. $\alpha = 10°$.

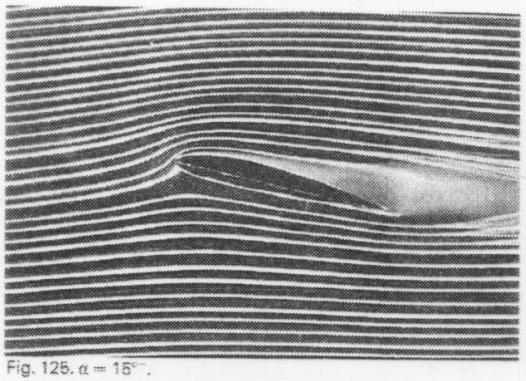


Fig. 125. $\alpha = 15°$.

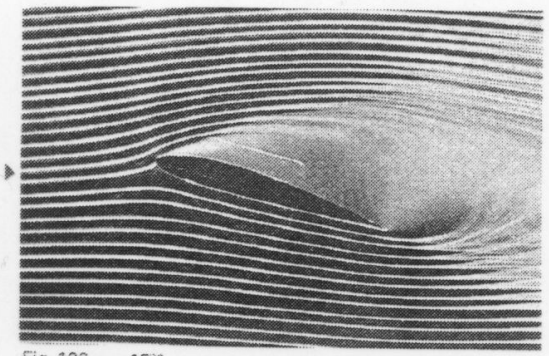
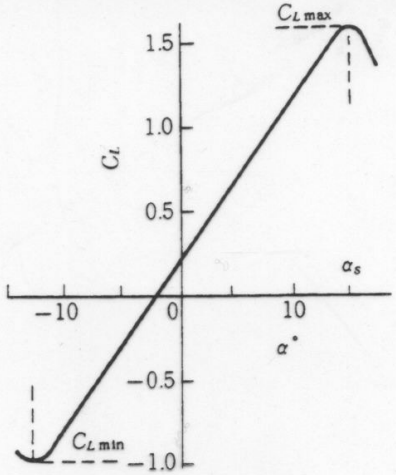


Fig. 126. $\alpha = 15°$.



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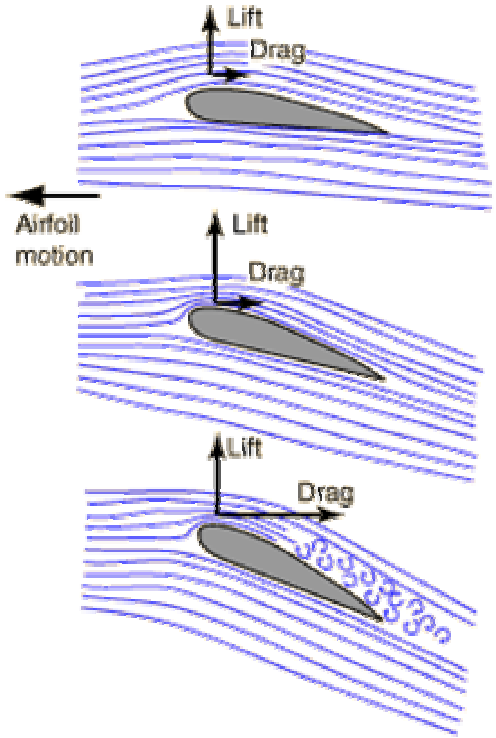
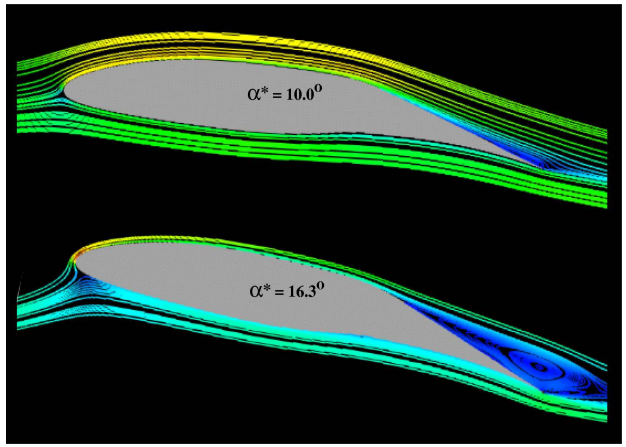
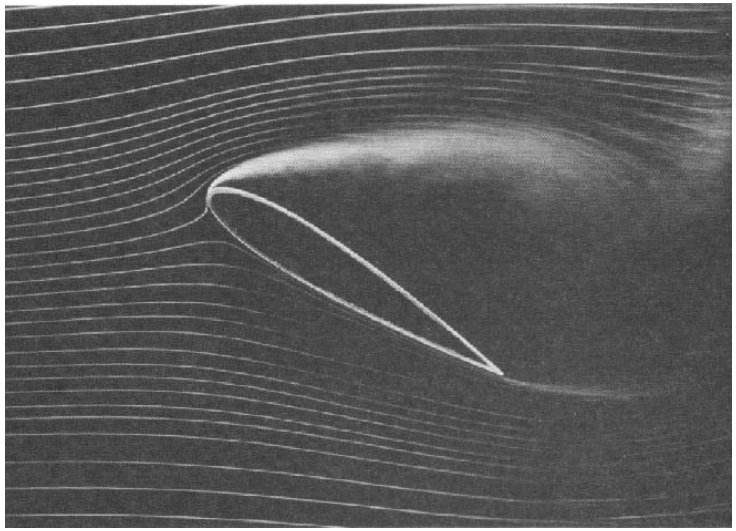
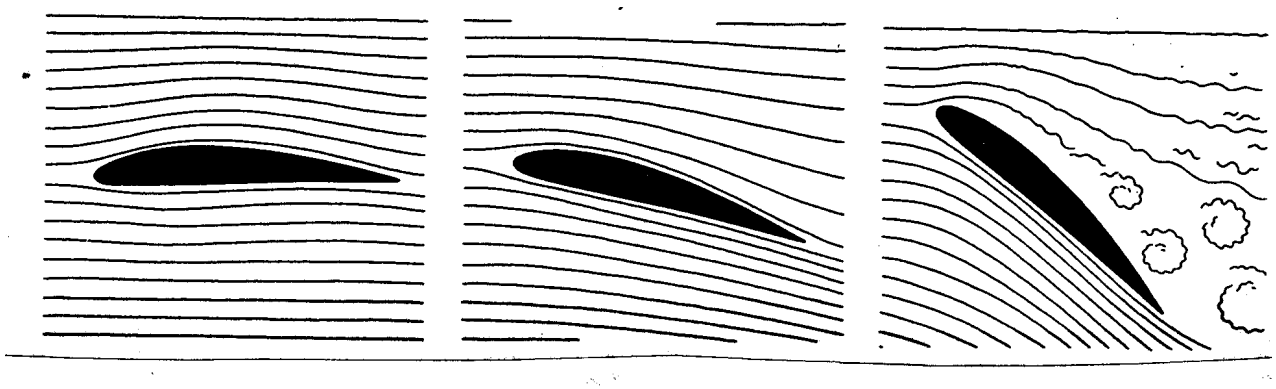
Entrada en pérdida (Stall)

A elevados ángulos de ataque se desprende las corriente y se pierden características superficie sustentadora (L/D >> 1)









Entrada en pérdida (Stall)

Figs. 138–141. Aerofoil with leading edge slat.

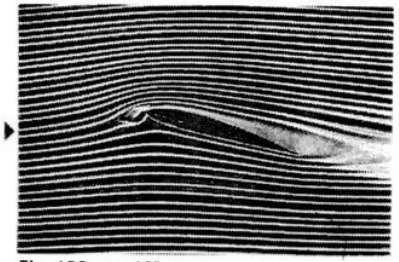


Fig. 138. $\alpha = 10°$.

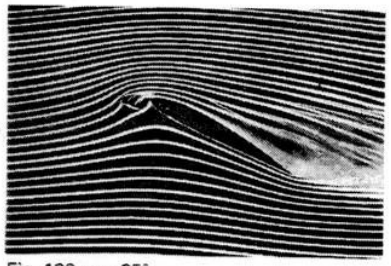


Fig. 139. $\alpha = 25°$.

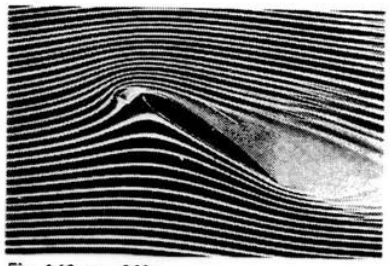


Fig. 140. $\alpha = 30°^-$.

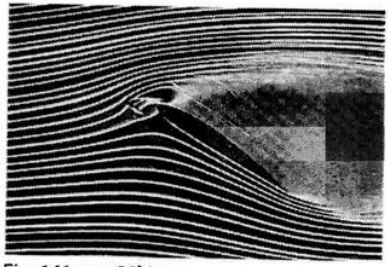


Fig. 141. $\alpha = 30°^+$.

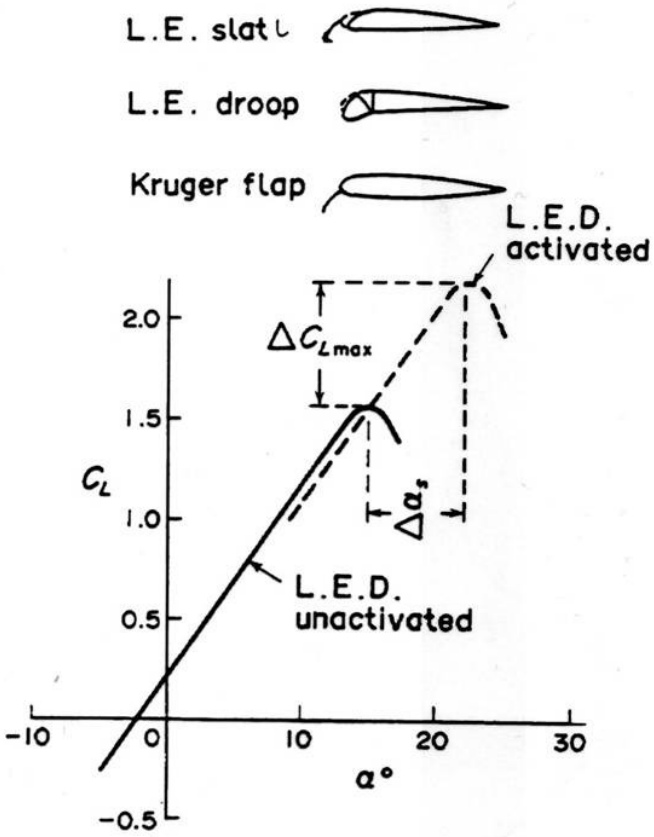


Fig. 138(a). Function of leading edge flap.

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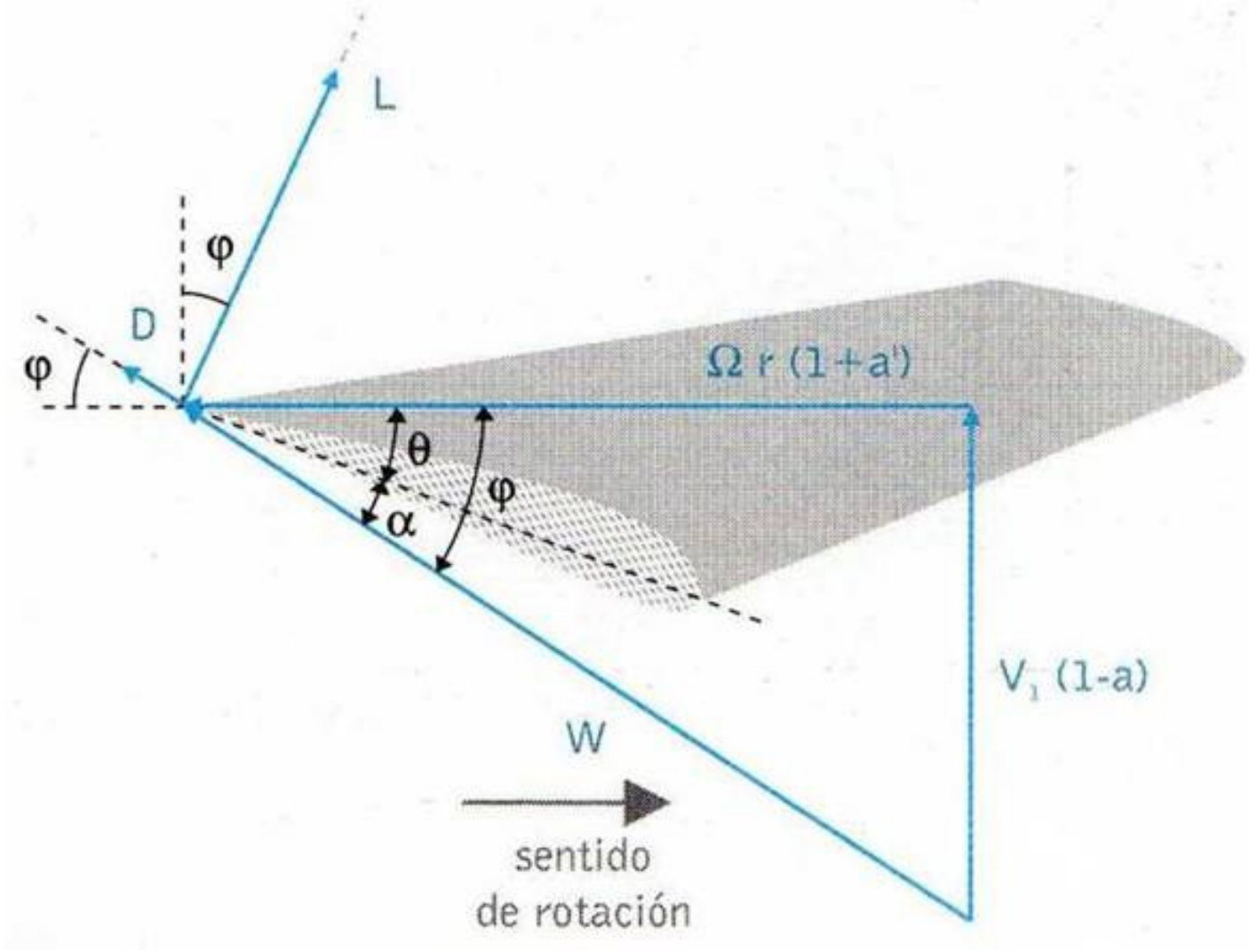
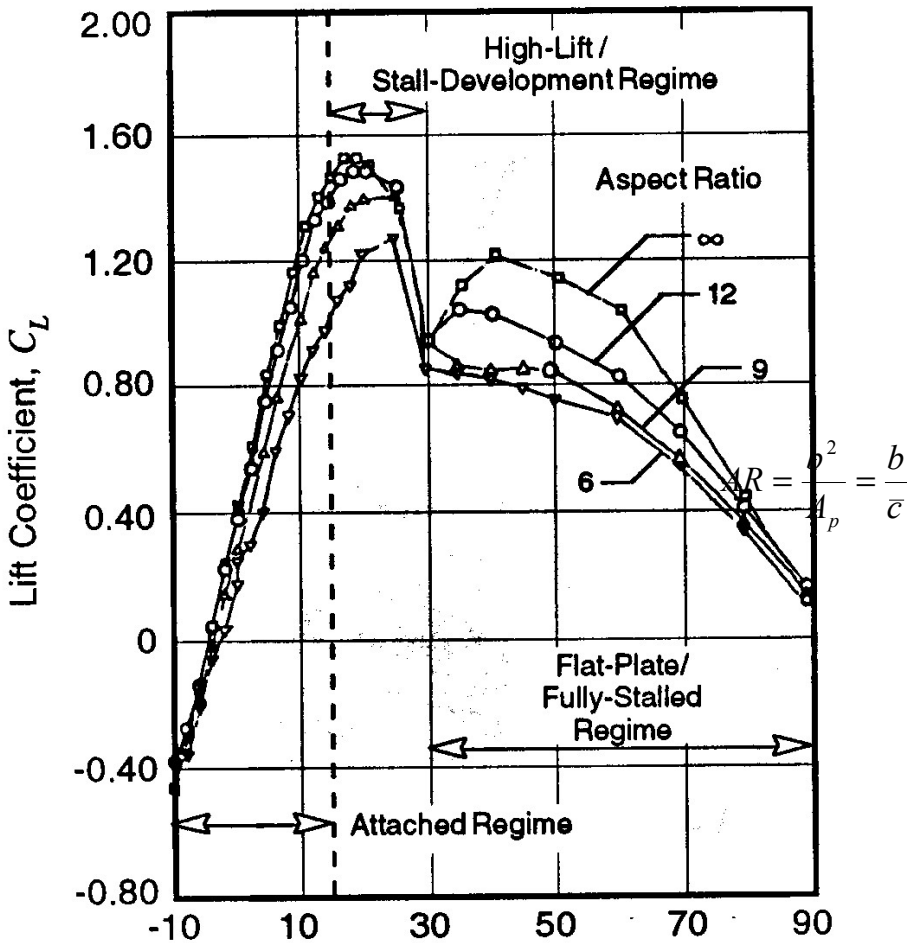
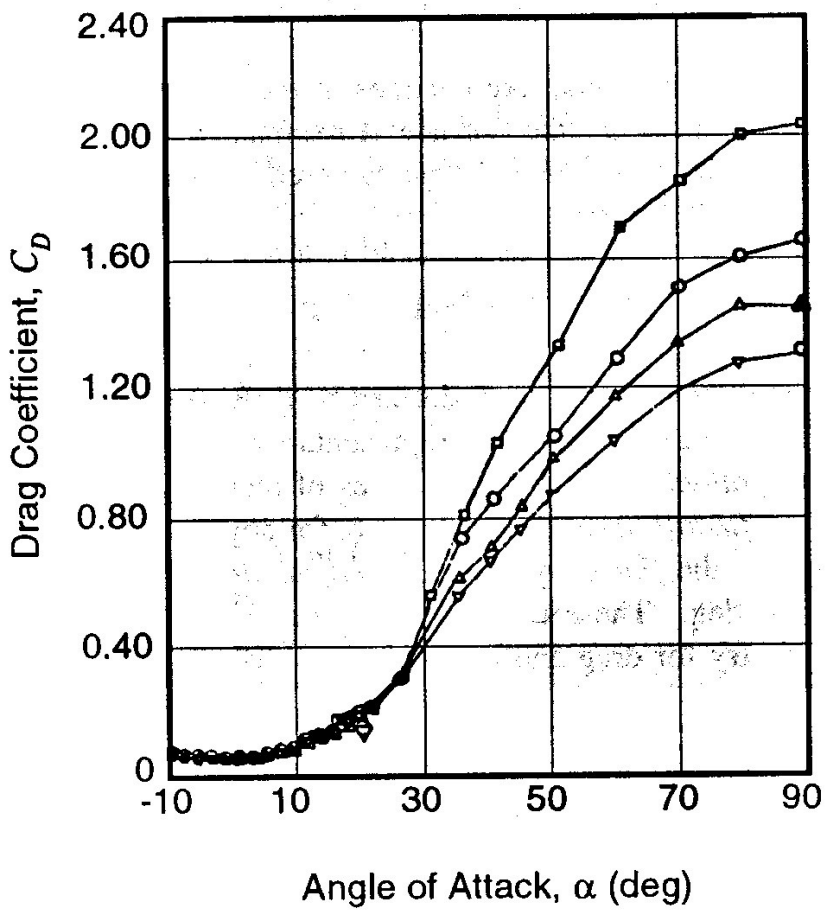
El perfil aerodinámico en un aerogenerador



Polares extendidas





NACA 4415
Re = 5.10^5

$$AR = \frac{b^2}{A_p} = \frac{b}{\bar{c}}$$

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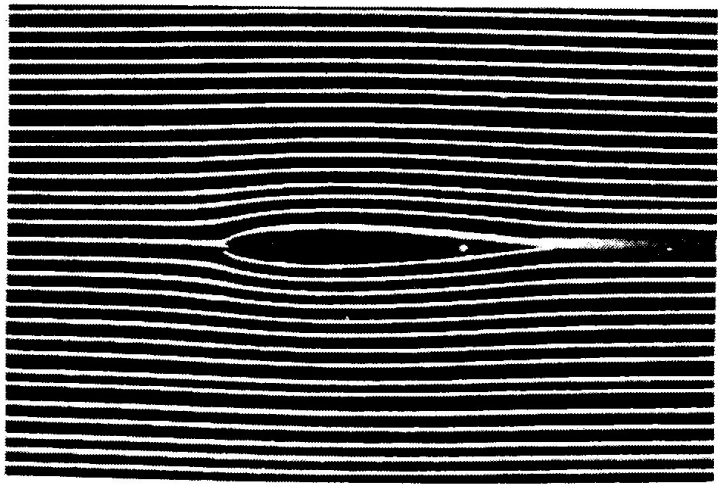
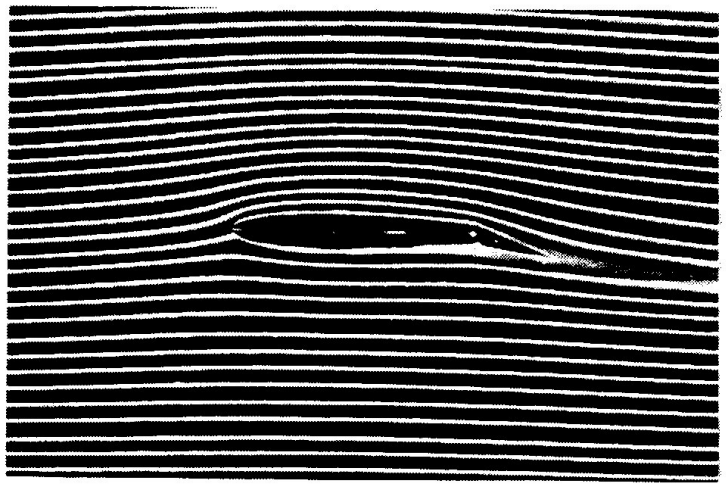
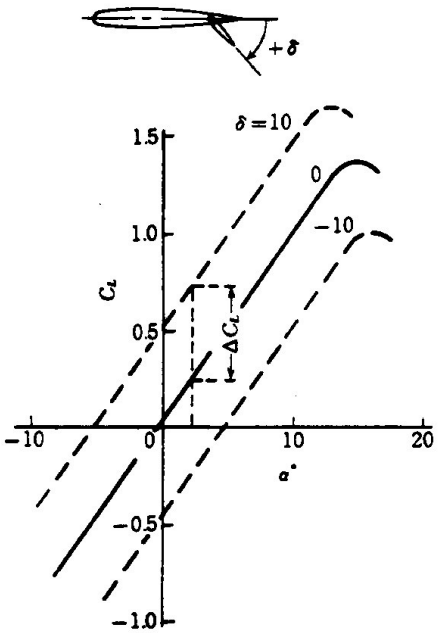
Alerones







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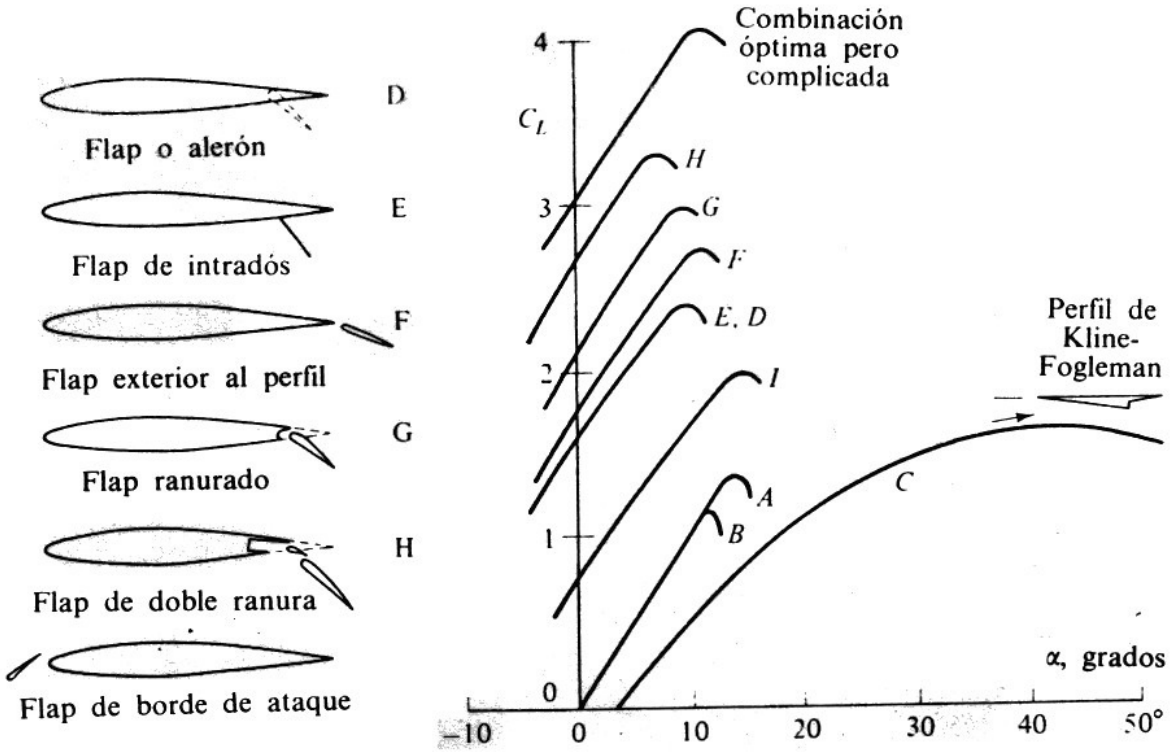
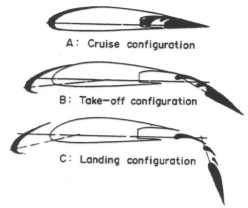
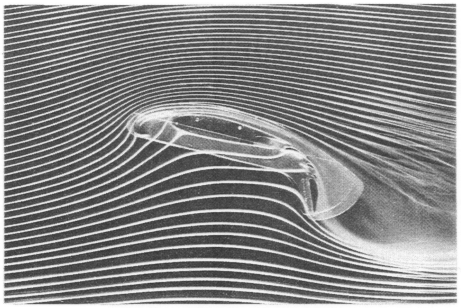
Hipersustentación

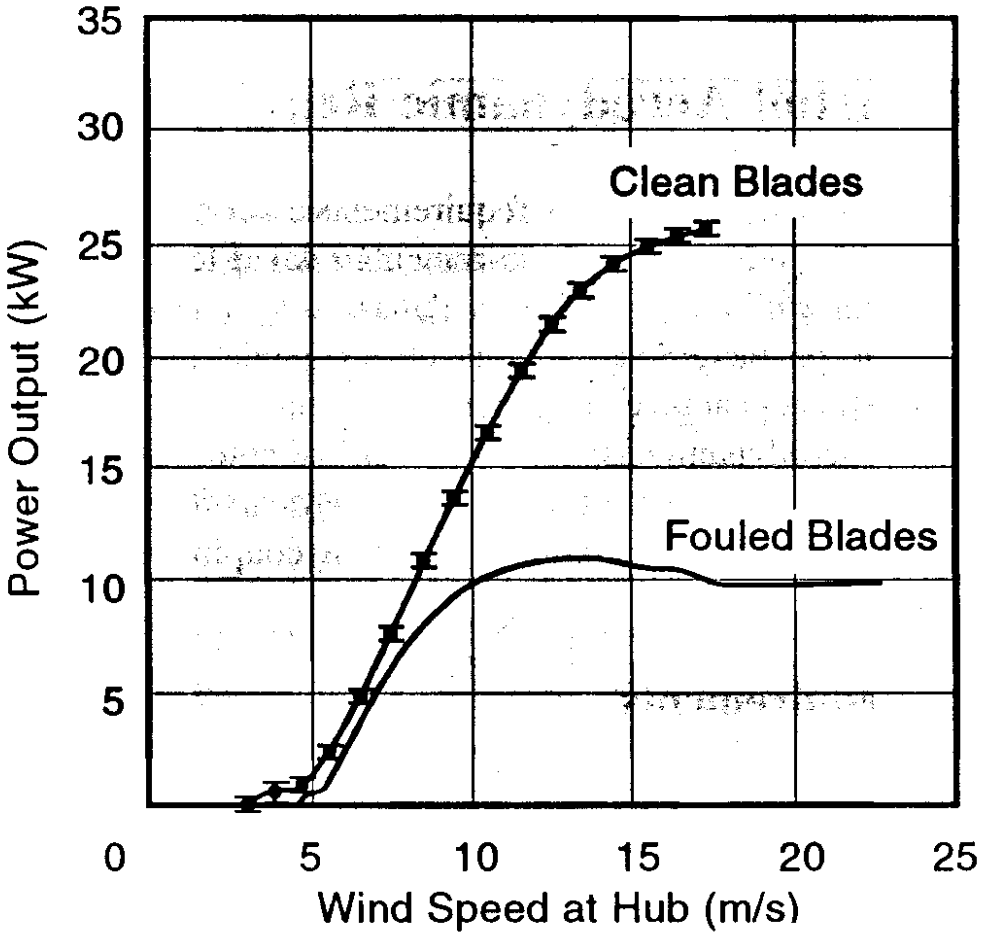






Pérdida actuaciones por ensuciamiento

El rotor eólico actúa en ambiente más sucio que otras aplicaciones



FX 84-W-151
- Lisa: $c_L/c_D = 165$
- Rugosa: $c_L/c_D = 63$

LS(1)-0415 MOD:
- Lisa: $c_L/c_D = 113$
- Rugosa: $c_L/c_D = 78$

Efecto del ensuciamiento de la pala por polvo, suciedad, e insectos en las actuaciones de un pequeño HAWT (D = 10 m)

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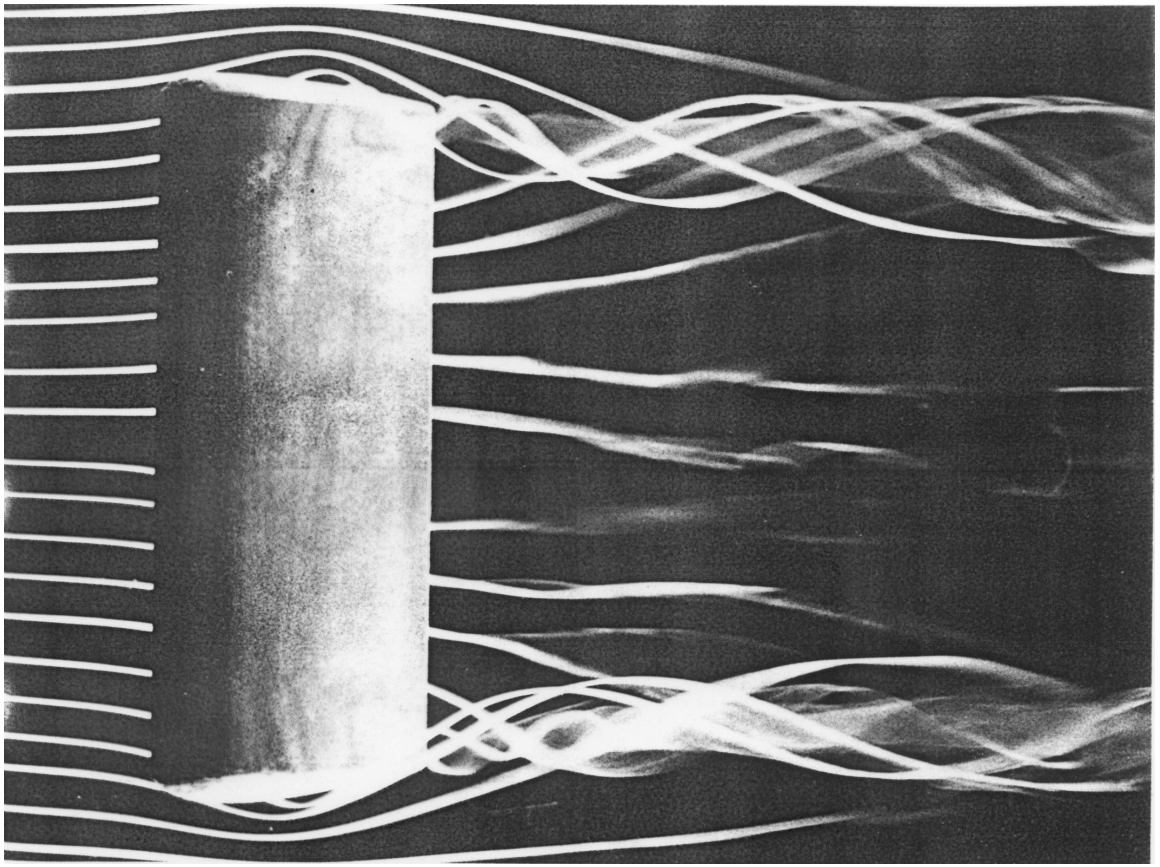
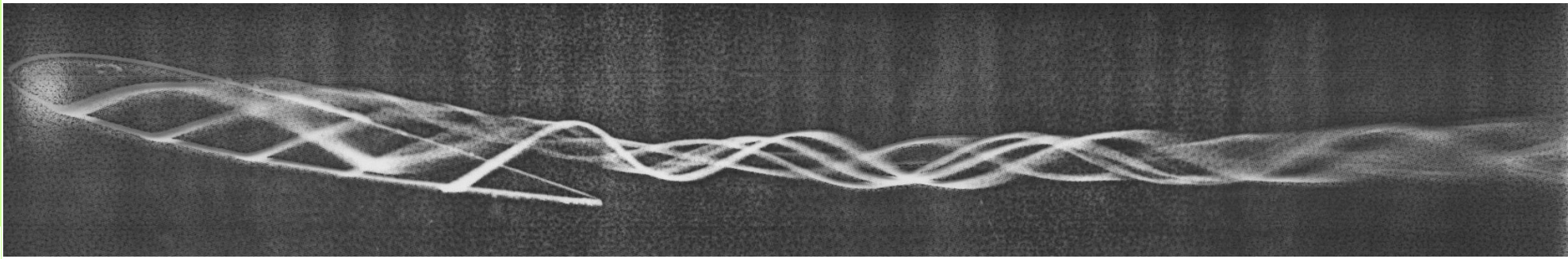
Pérdida punta de pala





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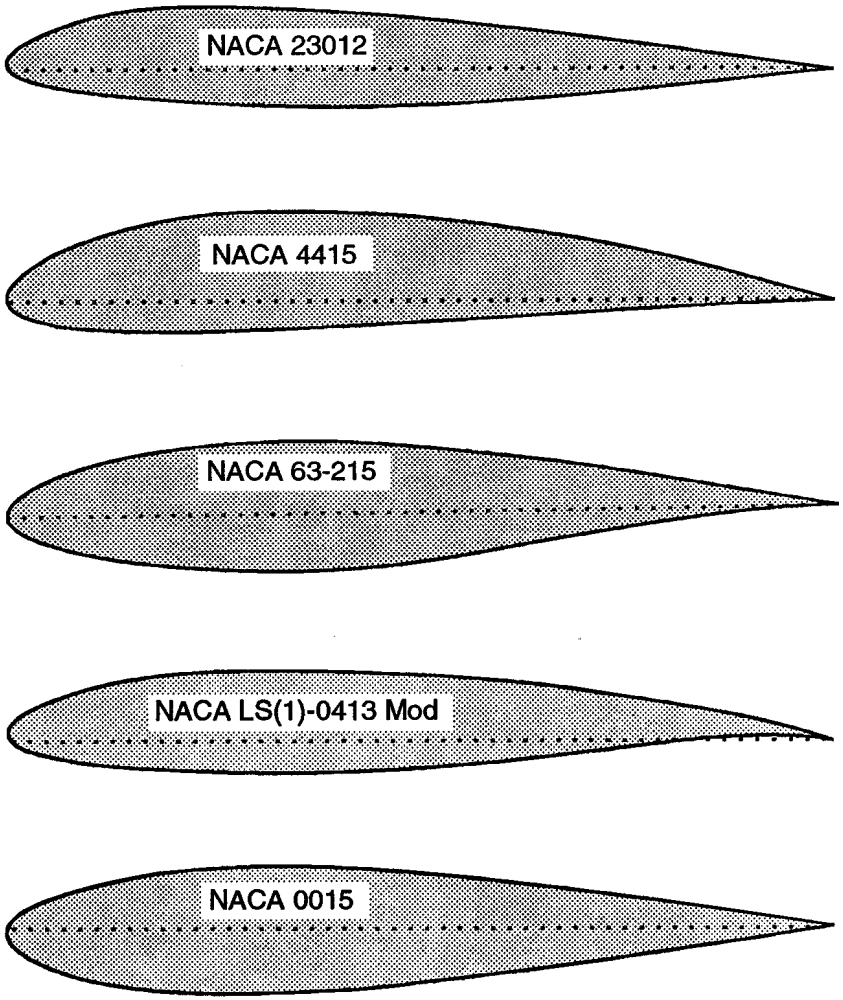
Perfiles aviación para eólica



- $c_{L,max}$ muy sensible a rugosidad
- Actuaciones caen muy rápido con espesor

- Muy usados en aerogeneradores

- Los mejores de serie NACA para aerogeneradores

- Desarrollado para baja sensibilidad a rugosidad.
- Grandes pérdidas por rugosidad en las máquinas que lo han implementado.

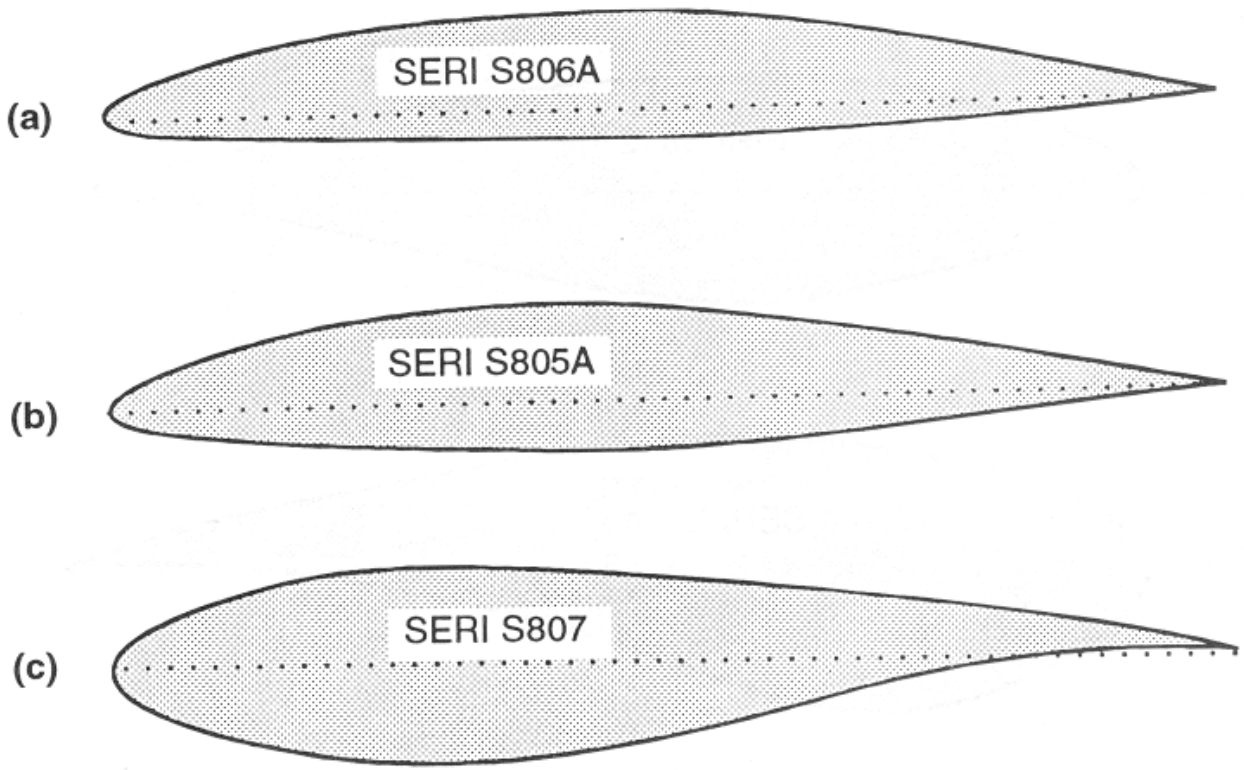
- Empleado en VAWT

Common wind turbine airfoils, designed originally for aircraft.

Características adecuadas perfil eólica

- **ε/c :**
  - Baja sensibilidad a cambios en rugosidad
  - Buen comportamiento con superficie rugosa
  - Sensibilidad creciente: NASA LS-1-Mod , NACA 44xx , NACA 230xx
  - Ángulo salida negativo en intradós reduce sensibilidad
  - Afecta más a las de paso fijo por anticipar desprendimiento
  - Máquinas grandes menos afectadas por ambiente más limpio y c ↑
- **c_L/c_D :**
  - Maximizar ⇒ Gran efecto sobre Cp
- **$c_{L,max}$:**
  - Pequeña dependencia rugosidad, para evitar picos potencia
  - Un valor crítico a partir del cual la producción energética ya no se ve afectada
- **c_m :**
  - Pequeño (torsión, mecanismo cambio paso)
- **t/c :**
  - Rigidez estructural
  - Perfil grueso → Aumentar espesor por intradós menos sensible.
- **Ω = cte**
  - Rango amplio de α manteniendo c_L/c_D elevado
- **λ = cte**
  - Perfiles de mayor c_L/c_D en menor rango α

Perfiles eólica pequeña potencia



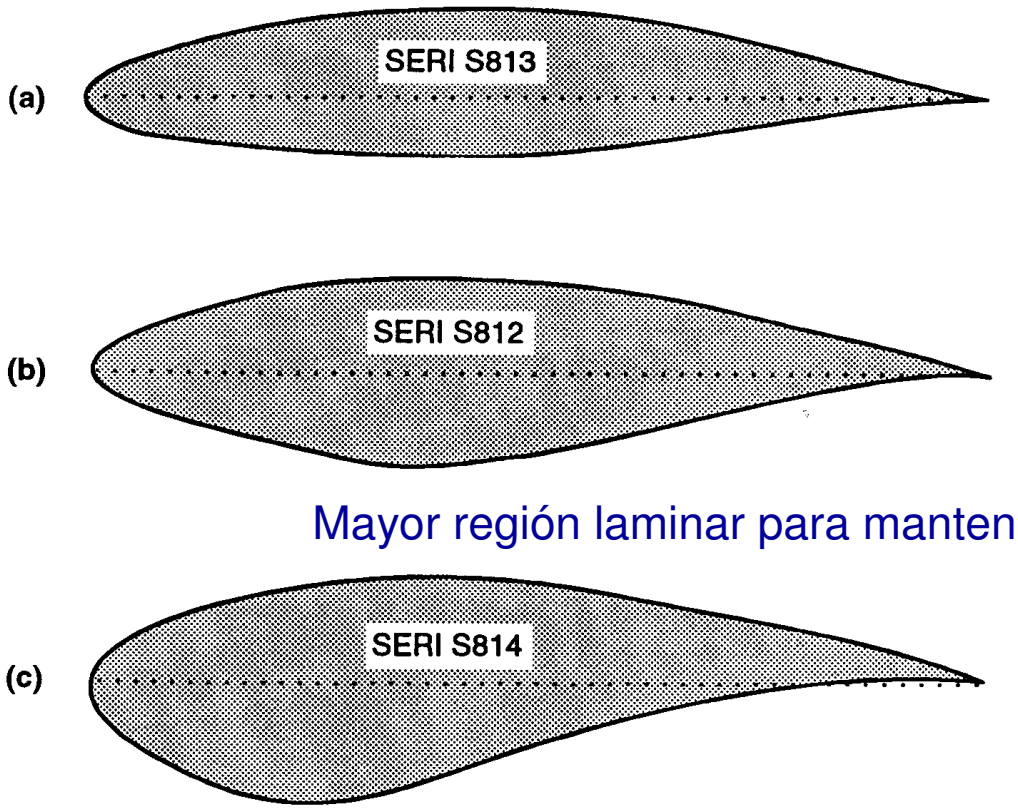
t/c = 0.135

Contours of the SERI S805A/S806A/S807 series of airfoils designed specifically for fixed-pitch HAWTs with diameters from 10 m to 20 m. (a) Tip region ($r/R \approx 0.95$) (b) Primary outboard airfoil ($r/R \approx 0.75$) (c) Root region ($r/R \approx 0.40$) [Tangler and Somers 1986, NREL 1994]

Perfiles eólica. Comparación con convencionales

Perfil	t/c (%)	$c_{L,max}$	$c_{D,min}$	c_L/c_D para c_L = 0,7	c_m (α=0)
SERI S805A	13.5	1.2	0.007	90	-0.05
NACA 4415	15.0	1.4	0.009	85	-0.08
NACA 23012	12.0	1.3	0.009	70	-0.01
LS(1)-04013 Mod	13.0	1.5	0.008	86	-0.10

Perfiles eólica media potencia



t/c = 0.21

Mayor región laminar para mantener c_D bajo con t/c mayor

Figure 6-8. Contours of the SERI S812/S813/S814 series of airfoils designed specifically for fixed-pitch HAWTs with diameters from 21 m to 35 m. (a) Tip region ($r/R \approx 0.95$) (b) Primary outboard airfoil ($r/R \approx 0.75$), (c) Root region ($r/R \approx 0.40$) [Tangler 1987, NREL 1994]

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Perfiles eólica gran potencia

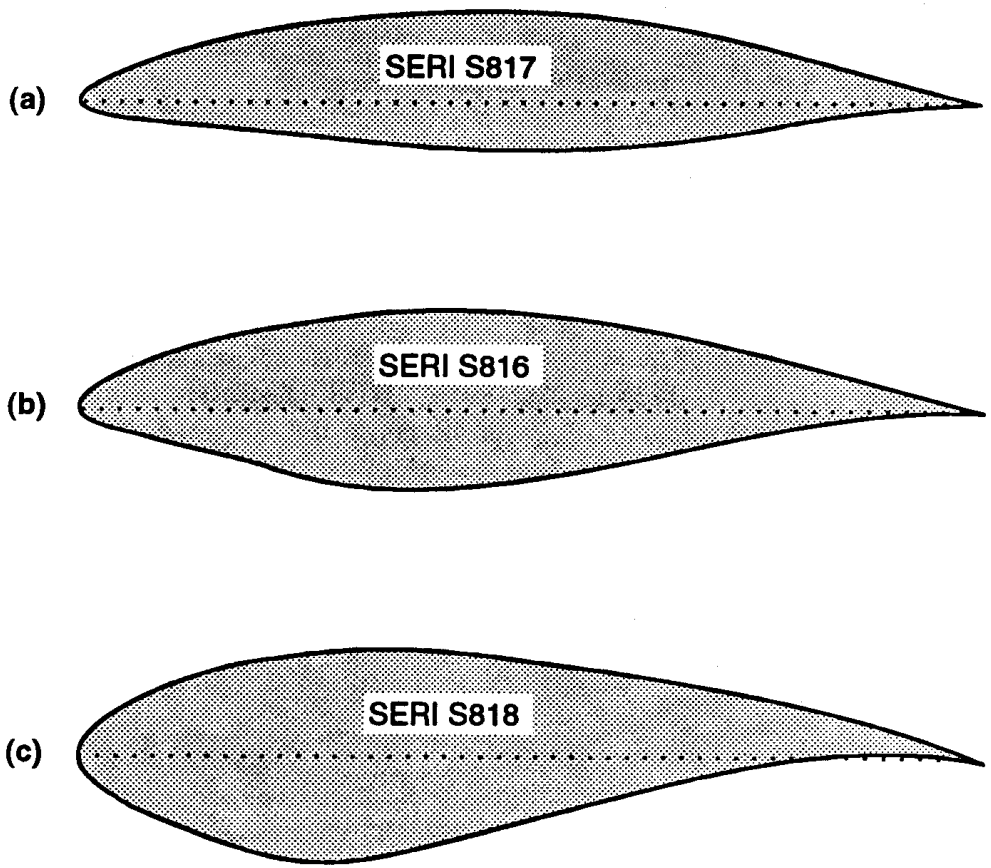

Figure 6-9. Contours of the SERI series of airfoils designed specifically for fixed-pitch HAWTs 36 m in diameter and larger. (a) Tip region ($r/R \approx 0.95$) (b) Primary outboard airfoil ($r/R \approx 0.75$) (c) Root region ($r/R \approx 0.40$) [NREL 1994]

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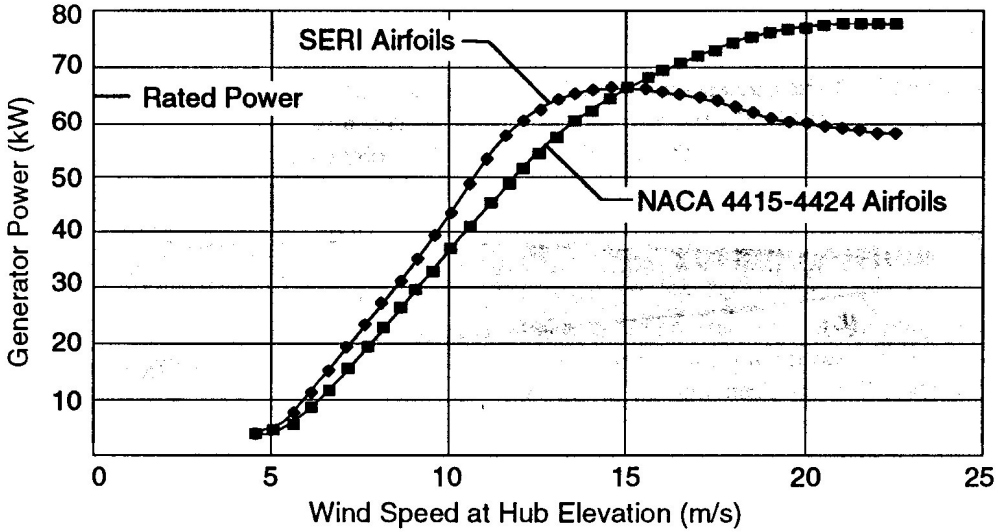
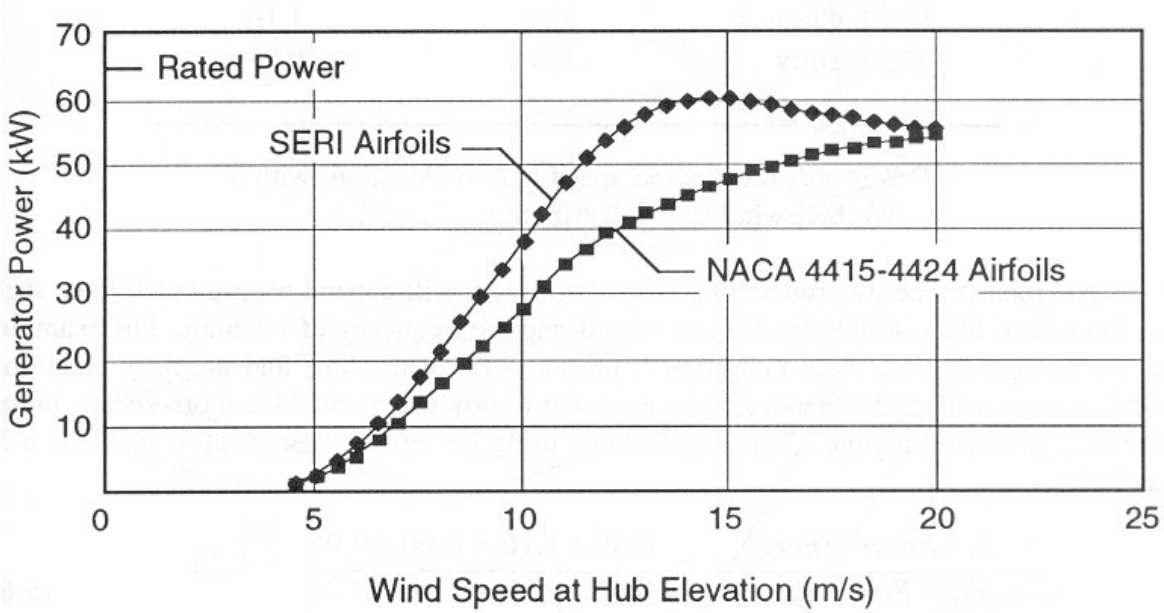
Comparación perfiles aviación / eólica



Perfiles limpios



Perfiles sucios

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