空气与气体动力学

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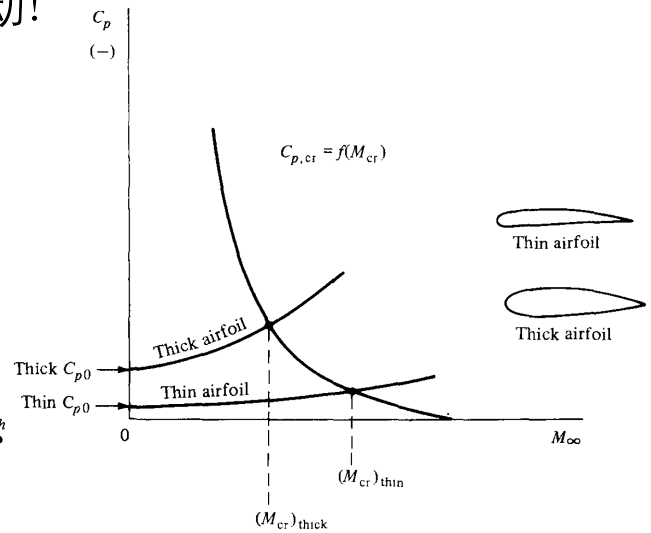
回顾：

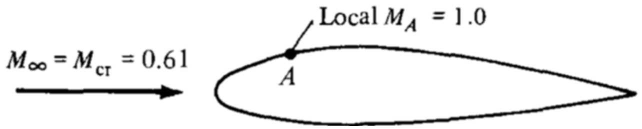
1. Prandtl-Glauert压缩性修正: $C_p = \frac{C_{p\,0}}{\sqrt{1-Ma_\infty^2}}$ $C_l = \frac{C_{l\,0}}{\sqrt{1-Ma_\infty^2}}$ $C_m = \frac{C_{m\,0}}{\sqrt{1-Ma_\infty^2}}$

相同翼型：(x,y)空间可压流动 → (ξ,η)空间不可压流动!

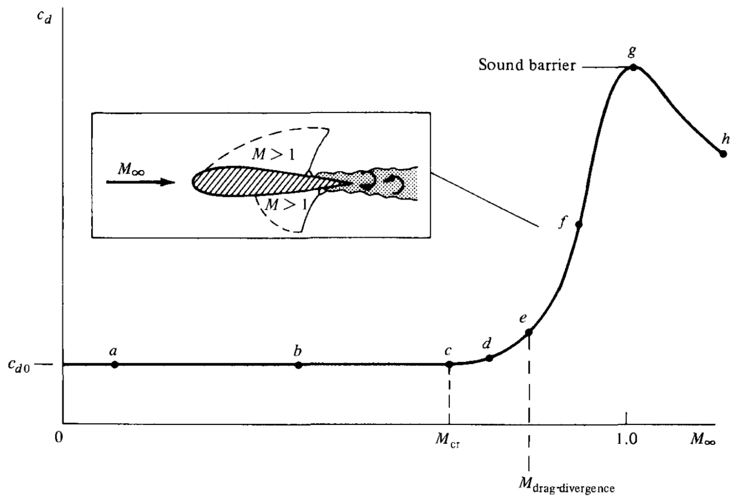
$$\beta^2\frac{\partial^2\hat{\phi}}{\partial x^2}+\frac{\partial^2\hat{\phi}}{\partial y^2}=0 \qquad \frac{\partial^2\bar{\phi}}{\partial \xi^2}+\frac{\partial^2\bar{\phi}}{\partial \eta^2}=0$$



2.临界马赫数：



3.阻力发散，声障



减C_d, C_{dmax}：

薄翼型；后掠翼。

超临界翼型；面积律。

4.超声速翼型特点

尖头尖尾、对称、薄；激波，膨胀波。

13.7超声速线化理论(10.9)

$$(1-Ma_\infty^2)\frac{\partial^2\hat{\phi}}{\partial x^2}+\frac{\partial^2\hat{\phi}}{\partial y^2}=0 \quad Ma_\infty<1\text{椭圆型方程} \quad Ma_\infty>1\text{双曲型方程}$$

1. 线化扰动速度势方程:

$$Ma_\infty>1: \qquad \lambda^2\frac{\partial^2\hat{\phi}}{\partial x^2}-\frac{\partial^2\hat{\phi}}{\partial y^2}=0 \qquad \lambda=\sqrt{Ma_\infty^2-1}$$

解为：$\hat{\phi}=f(x-\lambda y)$

$$\frac{\partial\hat{\phi}}{\partial x}=f'(x-\lambda y) \qquad \frac{\partial^2\hat{\phi}}{\partial x^2}=f''$$

$$\frac{\partial\hat{\phi}}{\partial y}=(-\lambda)f'(x-\lambda y) \qquad \frac{\partial^2\hat{\phi}}{\partial y^2}=\lambda^2 f''$$

$$\Rightarrow \lambda^2\frac{\partial^2\hat{\phi}}{\partial x^2}-\frac{\partial^2\hat{\phi}}{\partial y^2}=\lambda^2 f''-\lambda^2 f''=0$$

$\Rightarrow$ $\hat{\phi}=f(x-\lambda y)$为$\lambda^2\frac{\partial^2\hat{\phi}}{\partial x^2}-\frac{\partial^2\hat{\phi}}{\partial y^2}=0$的解。

13.7超声速线化理论(10.9)

1. 线化扰动速度势方程:

$$Ma_\infty > 1: \quad \lambda^2 \frac{\partial^2 \hat{\phi}}{\partial x^2} - \frac{\partial^2 \hat{\phi}}{\partial y^2} = 0 \qquad \lambda = \sqrt{Ma_\infty^2 - 1}$$

$$\hat{\phi} = f(x - \lambda y)\text{为解!}$$

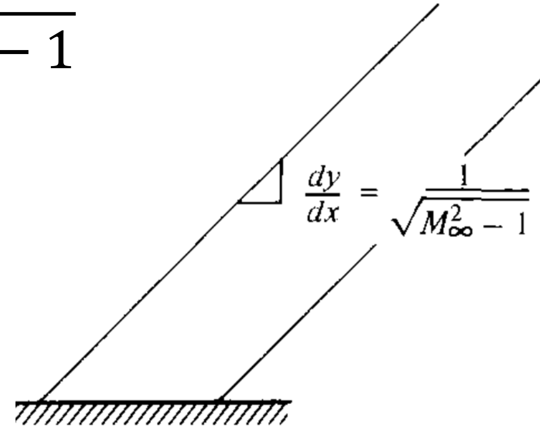
$\hat{\phi}$沿$x - \lambda y = C$ 为 常数 。

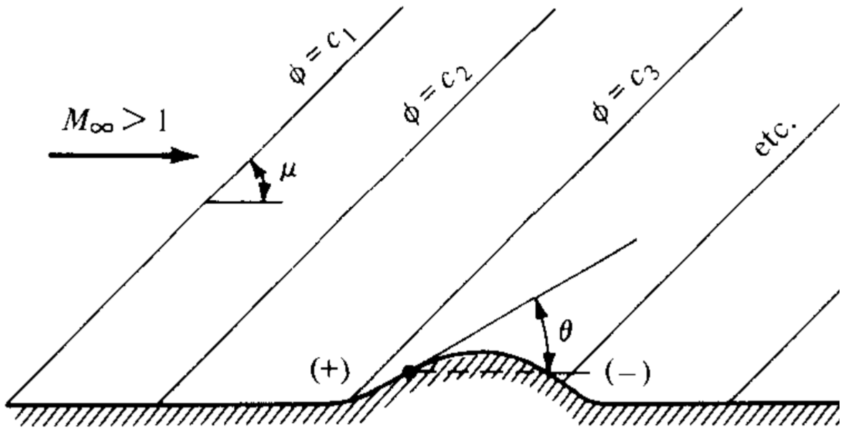
$x - \lambda y = C$是斜率$\dfrac{dy}{dx} = \dfrac{1}{\lambda} = \dfrac{1}{\sqrt{Ma_\infty^2 - 1}}$的直线。

$tan\mu = \dfrac{1}{\sqrt{Ma_\infty^2 - 1}}$,$\mu$为马赫角。

$\hat{\phi}$沿马赫线为常数，小扰动沿Ma线传播！

适用: 线化超声流（小扰动），不适用激波、膨胀波。





$Ma_\infty > 1$扰动无法向上游传播。

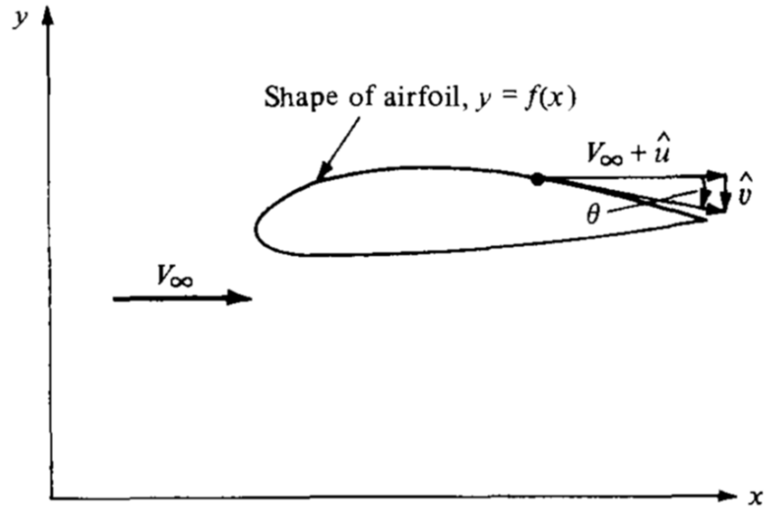
13.7超声速线化理论(10.9)

$$\lambda^2 \frac{\partial^2 \hat{\phi}}{\partial x^2} - \frac{\partial^2 \hat{\phi}}{\partial y^2} = 0 \qquad \hat{\phi} = f(x - \lambda y)$$

2. 线化C_p: $C_p = -\dfrac{2\hat{u}}{V_\infty}$

势流场中：

$$\left.\begin{aligned} \hat{u} &= \frac{\partial \hat{\phi}}{\partial x} = f' \\ \hat{v} &= \frac{\partial \hat{\phi}}{\partial y} = -\lambda f' \end{aligned}\right\} \hat{u} = -\frac{\hat{v}}{\lambda}$$



翼面上：$\hat{v} \approx V_\infty tan\theta \approx V_\infty \theta$

翼面上：$\hat{u} = -\dfrac{V_\infty \theta}{\lambda}$

$$C_p = -\frac{2\hat{u}}{V_\infty} = \frac{2\theta}{\lambda} = \frac{2\theta}{\sqrt{Ma_\infty^2 - 1}}$$ 超声速线化压强系数！

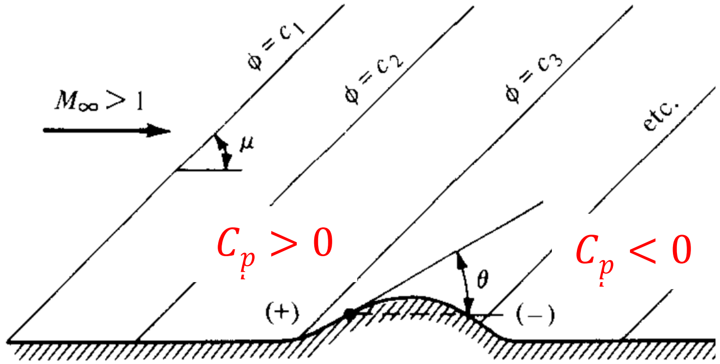
$$\boxed{C_p = \frac{2\theta}{\sqrt{Ma_\infty^2 - 1}}}$$ C_p仅与θ、Ma_∞有关！一级近似。

13.7超声速线化理论(10.9)

2. 线化C_p:

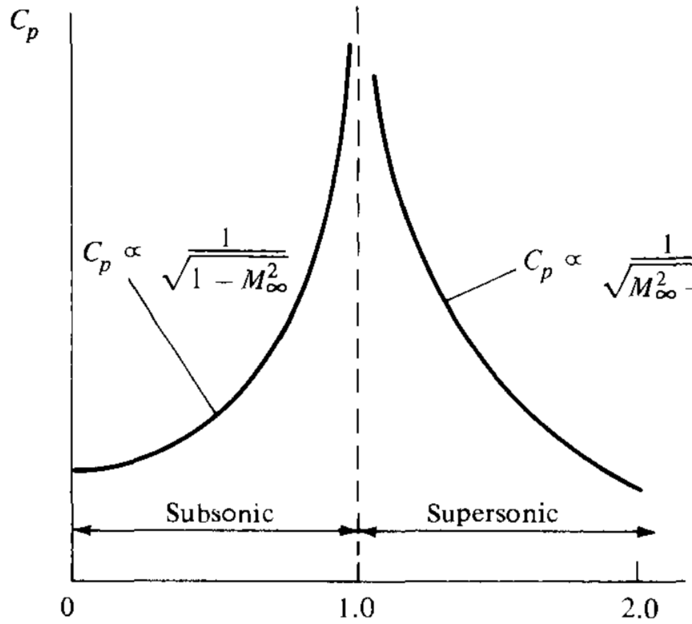
$$\boxed{C_p=\frac{2\theta}{\sqrt{Ma_\infty^2-1}}}$$

$Ma_\infty>1$



（1） $C_p\propto\theta$: 突起前高压，后低压； →波阻

（2） $C_p\propto\frac{1}{\sqrt{Ma_\infty^2-1}}$: Ma_∞↑ C_p↓；



$$\boxed{\text{亚声速：}C_p=\frac{C_{p,0}}{\sqrt{1-Ma_\infty^2}}}$$

超声速C_p与θ、Ma_∞有关。

13.7超声速线化理论(10.9)

$$C_p = \frac{2\theta}{\sqrt{Ma_\infty^2 - 1}} \quad Ma_\infty > 1$$

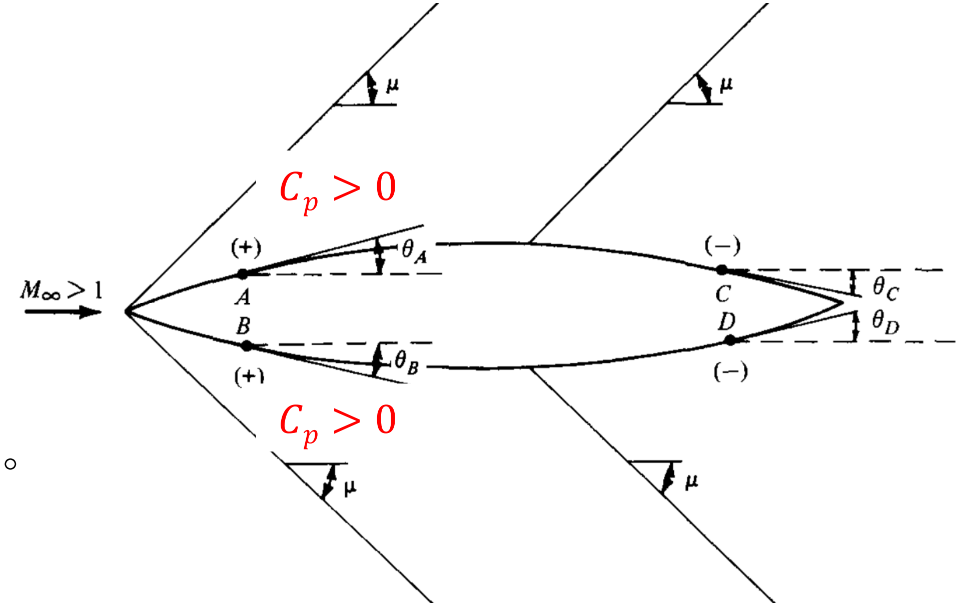
3. 超声速翼型理论:

$$\theta = \frac{dy}{dx}: \text{上表面}\frac{dy}{dx} > 0, \text{下表面}\frac{dy}{dx} < 0。$$

$$C_p = \frac{\pm 2\theta}{\sqrt{Ma_\infty^2 - 1}}$$

+ :壁面向气流内折；－：壁面远离气流外折。

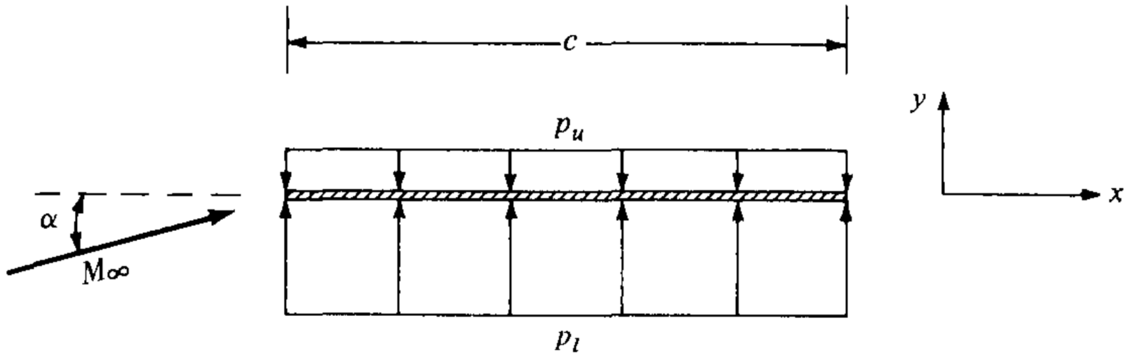
$$C_{p,u} = \frac{2\frac{dy}{dx}}{\sqrt{Ma_\infty^2 - 1}} \qquad C_{p,l} = \frac{-2\frac{dy}{dx}}{\sqrt{Ma_\infty^2 - 1}}$$



13.7超声速线化理论(10.9)

3. 超声速翼型理论: $C_p = \frac{\pm 2\theta}{\sqrt{Ma_\infty^2 - 1}}$

1)平板: $C_{p,u} = \frac{-2\alpha}{\sqrt{Ma_\infty^2 - 1}}$



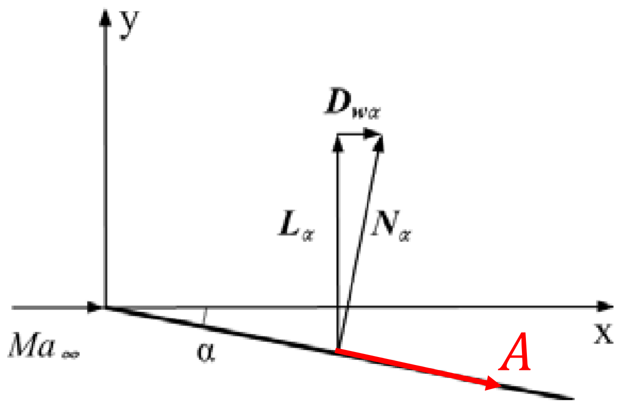
$$C_{p,l} = \frac{2\alpha}{\sqrt{Ma_\infty^2 - 1}}$$

$$\Delta C_{p,\alpha} = C_{p,l} - Cp_{,u} = \frac{4\alpha}{\sqrt{Ma_\infty^2 - 1}} = \frac{4\alpha}{B}$$

$$B = \frac{1}{\sqrt{Ma_\infty^2 - 1}}$$

$$C_n = \frac{1}{c}\int_0^c (C_{p,l} - C_{p,u})\, dx$$

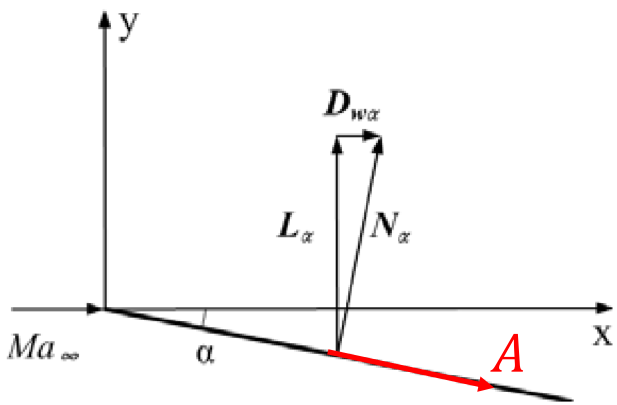
$$= \frac{4\alpha}{\sqrt{Ma_\infty^2 - 1}} \frac{1}{c}\int_0^c dx \quad = \frac{4\alpha}{\sqrt{Ma_\infty^2 - 1}}$$



$$C_a = 0$$

13.7超声速线化理论(10.9)

3. 超声速翼型理论:



1)平板: $C_n = \dfrac{4\alpha}{\sqrt{Ma_\infty^2-1}}$ $\quad C_a = 0$

$$C_l = C_n cos\alpha - C_a sin\alpha$$

$$C_d = C_n sin\alpha + C_a cos\alpha$$

$sin\alpha \approx \alpha,\ cos\alpha \approx 1$

$\Rightarrow$ $C_l = C_n \quad C_d = C_n\alpha$

Ma_∞>1, 平板: $\boxed{C_l = \dfrac{4\alpha}{\sqrt{Ma_\infty^2-1}}}$ $\boxed{C_d = \dfrac{4\alpha^2}{\sqrt{Ma_\infty^2-1}}}$ 无粘：波阻!

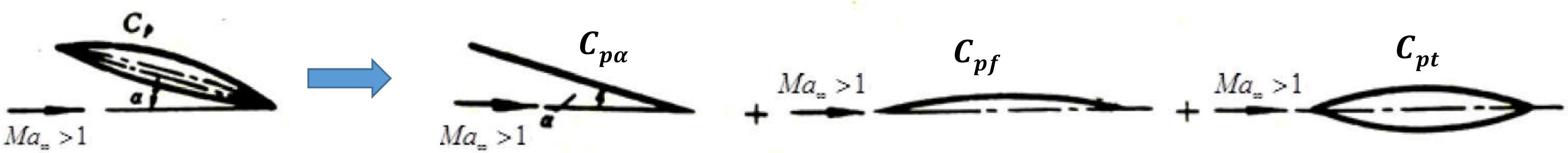
$C_d = C_l\alpha$ 升致波阻!

Ma_∞<1无粘： C_d =0!!

13.7超声速线化理论(10.9)

$C_{p,u}=\frac{2\theta}{B}$ $C_{p,l}=\frac{-2\theta}{B}$ $B=\sqrt{Ma_\infty^2-1}$

4. 线化压强系数叠加（迎角、弯度、厚度）：



$$C_p=C_{p\alpha}+C_{pf}+C_{pt}$$

α:迎角为α的平板绕流；

f:迎角为0，中弧线弯度为f的弯板绕流；

t:迎角、弯度均为0，厚度为t的翼型绕流。

$$C_{p,u}=C_{p\alpha,u}+C_{pf,u}+C_{pt,u}=\frac{2}{B}[(\frac{dy_\alpha}{dx})_u+(\frac{dy_f}{dx})_u+(\frac{dy_t}{dx})_u]$$

$$C_{p,l}=C_{p\alpha,l}+C_{pf,l}+C_{pt,l}=\frac{-2}{B}[(\frac{dy_\alpha}{dx})_l+(\frac{dy_f}{dx})_l+(\frac{dy_t}{dx})_l]$$

13.7超声速线化理论(10.9)

$$C_{p,u} = \frac{2\theta}{B} \quad C_{p,l} = \frac{-2\theta}{B} \quad B = \sqrt{Ma_\infty^2 - 1}$$

4. 线化压强系数叠加（迎角、弯度、厚度）：

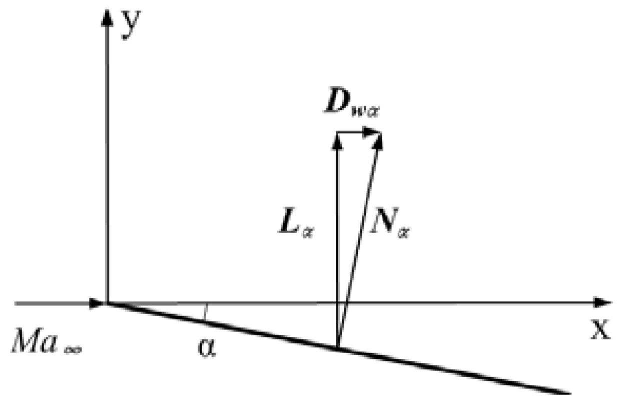
$$C_p = C_{p\alpha} + C_{pf} + C_{pt}$$

1) 平板绕流($C_{p\alpha}$)：

$$C_{p\alpha,u} = \frac{2}{B}\left(\frac{dy_\alpha}{dx}\right)_u = \frac{-2\alpha}{B}$$

$$C_{p\alpha,l} = \frac{-2}{B}\left(\frac{dy_\alpha}{dx}\right)_u = \frac{2\alpha}{B}$$

$$\Delta C_{p\alpha} = \frac{4\alpha}{B} \qquad B = \sqrt{Ma_\infty^2 - 1}$$



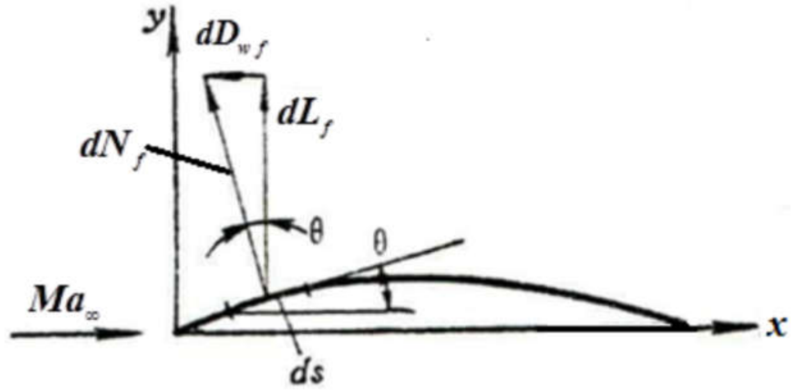
13.7超声速线化理论(10.9)

$$C_{p,u} = \frac{2\theta}{B} \quad C_{p,l} = \frac{-2\theta}{B} \quad B = \sqrt{Ma_\infty^2 - 1}$$

4. 线化压强系数叠加（迎角、弯度、厚度）：

$$C_p = C_{p\alpha} + C_{pf} + C_{pt}$$

2) 弯板绕流(C_{pf})：



$$C_{pf,u} = \frac{2}{B}\left(\frac{dy_f}{dx}\right)_u$$

$$C_{pf,l} = \frac{-2}{B}\left(\frac{dy_f}{dx}\right)_l \quad \text{上下面} \left(\frac{dy_f}{dx}\right)_u = \left(\frac{dy_f}{dx}\right)_l$$

$$\Delta C_{pf} = \frac{-4}{B}\left(\frac{dy_f}{dx}\right) \quad B = \sqrt{Ma_\infty^2 - 1}$$

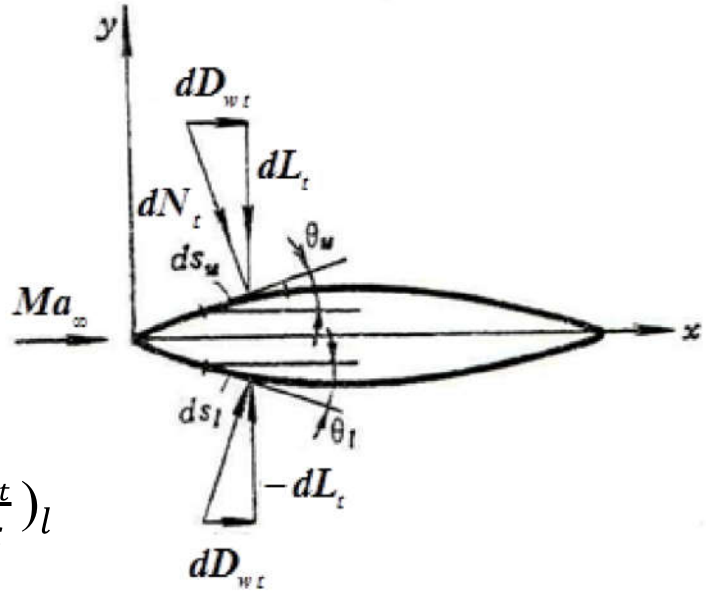
13.7超声速线化理论(10.9)

$C_{p,u}=\frac{2\theta}{B}$ $C_{p,l}=\frac{-2\theta}{B}$ $B=\sqrt{Ma_\infty^2-1}$

4. 线化压强系数叠加（迎角、弯度、厚度）：

$$C_p=C_{p\alpha}+C_{pf}+C_{pt}$$

3) 厚度影响(C_{pt})：



$$C_{pt,u}=\frac{2}{B}\left(\frac{dy_t}{dx}\right)_u$$

$$C_{pt,l}=\frac{-2}{B}\left(\frac{dy_t}{dx}\right)_l$$

上下面对称$\left(\frac{dy_t}{dx}\right)_u=-\left(\frac{dy_t}{dx}\right)_l$

$$\Delta C_{pt}=0$$

厚度引起的压差载荷为0!!

13.7超声速线化理论(10.9)

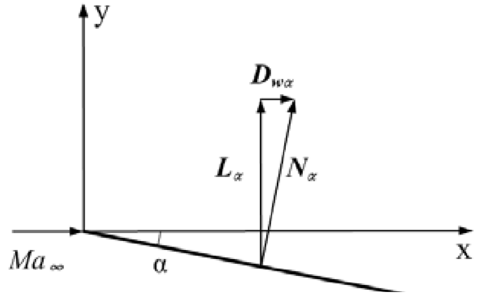
$$C_{p,u}=\frac{2\theta}{B}\qquad C_{p,l}=\frac{-2\theta}{B}\qquad B=\sqrt{Ma_\infty^2-1}$$

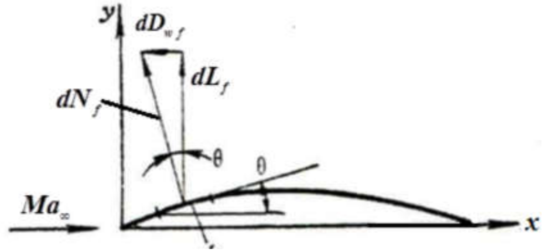
4. 线化压强系数叠加（迎角、弯度、厚度）：

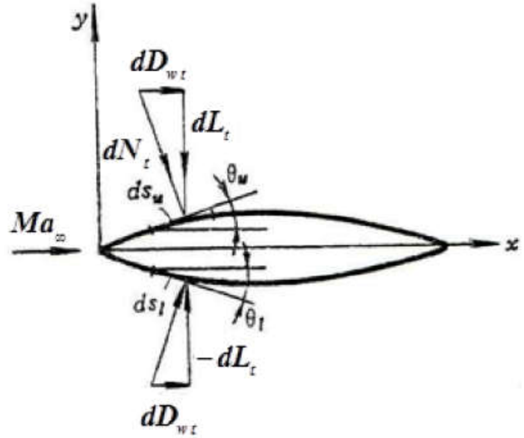
$$C_p=C_{p\alpha}+C_{pf}+C_{pt}$$

$$\Delta C_{p\alpha}=\frac{4\alpha}{B}\qquad \Delta C_{pf}=\frac{-4}{B}\left(\frac{dy_f}{dx}\right)\qquad \Delta C_{pt}=0$$

$$\Delta C_p=\Delta C_{p\alpha}+\Delta C_{pf}+\Delta C_{pt}$$
$$=\frac{4\alpha}{B}-\frac{4}{B}\left(\frac{dy_f}{dx}\right)$$







13.7超声速线化理论(10.9) $\Delta C_p = \Delta C_{p\alpha} + \Delta C_{pf} + \Delta C_{pt} = \frac{4\alpha}{B} - \frac{4}{B}\left(\frac{dy_f}{dx}\right)$

5. C_l: $C_l = C_{l\alpha} + C_{lf} + C_{lt}$

$$C_{l\alpha} = \frac{1}{c}\int_0^c \Delta C_{p\alpha}\, dx/\cos\alpha \cdot \cos\alpha$$

$$= \frac{1}{c}\int_0^c \Delta C_{p\alpha}\, dx$$

$$= \frac{4\alpha}{B}$$

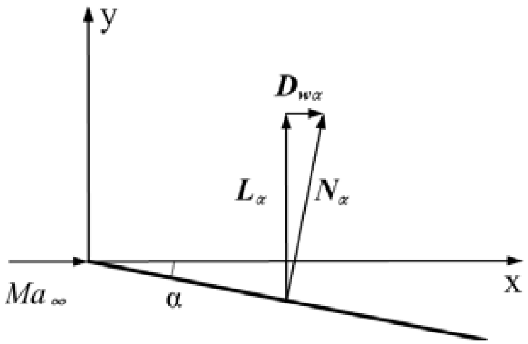
$$C_{lf} = \frac{1}{c}\int_0^c \Delta C_{pf}\, ds\cos\theta$$

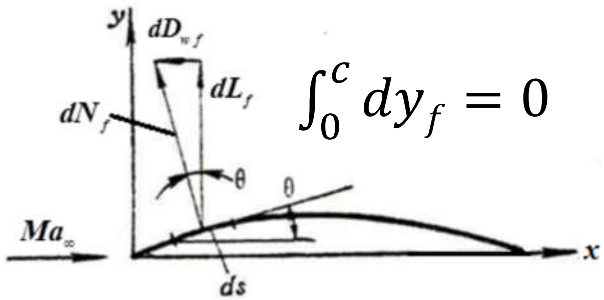
$$= \frac{1}{c}\int_0^c -\frac{4}{B}\left(\frac{dy_f}{dx}\right) dx$$

$$= \frac{1}{c}\int_0^c -\frac{4}{B} dy_f$$

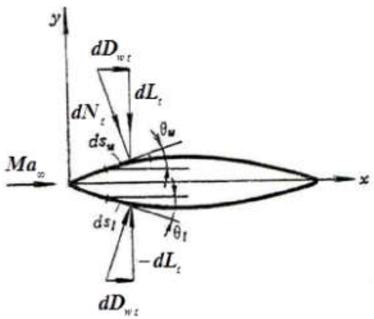
$$= -\frac{4}{Bc}\int_0^c dy_f \quad = 0$$

$\Delta C_{pt}=0 \rightarrow C_{lt} = 0$





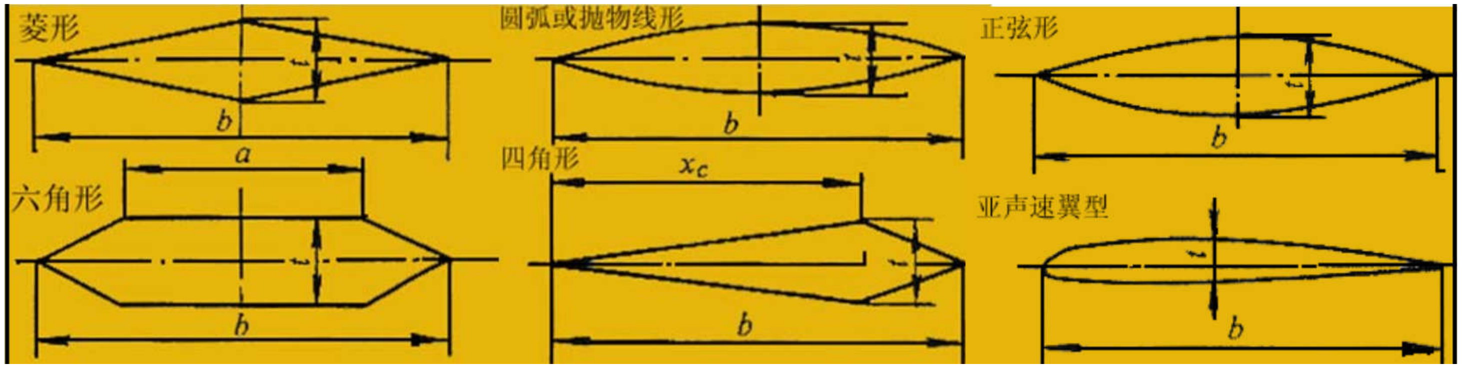
$\int_0^c dy_f = 0$



13.7超声速线化理论(10.9)

5\. C_l: $C_l = C_{l\alpha} + C_{lf} + C_{lt}$ $C_{l\alpha} = \frac{4\alpha}{B}$ $C_{lf} = 0$ $C_{lt} = 0$ 弯度、厚度对升力无贡献！

$\boxed{C_l = \frac{4\alpha}{B}}$ 超声速翼型：升力由α决定，与f,t无关！



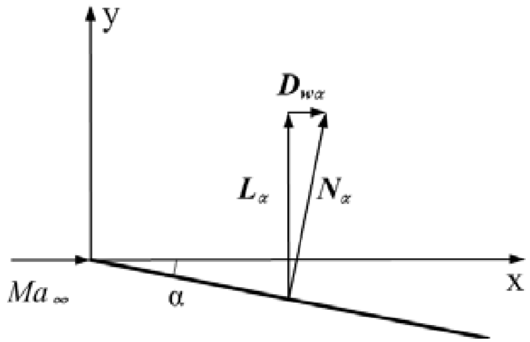
超声速翼型：无弯度对称、厚度小！

13.7超声速线化理论(10.9)

$\boxed{C_l = \frac{4\alpha}{B}}$ 超声速翼型：升力由α决定，与f,t无关！弯度、厚度对升力无贡献！

6. C_{dw}： $C_{dw} = C_{dw\alpha} + C_{dwf} + C_{dwt}$ （波阻）

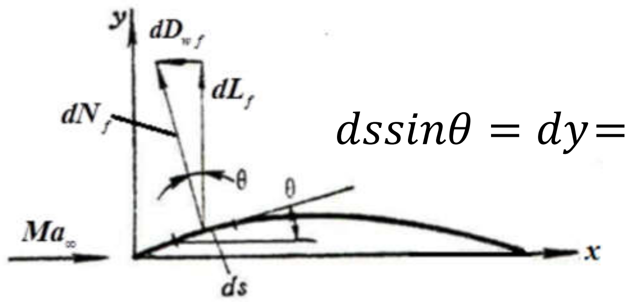
$$C_{dw\alpha} = C_{l\alpha}\alpha = \frac{4\alpha^2}{B}$$ 升致波阻!



$$C_{dwf} = \frac{1}{c}\int_0^c -\Delta C_{pf}\, ds\sin\theta$$

$$= \frac{1}{c}\int_0^c \frac{4}{B}\left(\frac{dy_f}{dx}\right)\left(\frac{dy_f}{dx}\right) dx$$

$$= \frac{4}{cB}\int_0^c \left(\frac{dy_f}{dx}\right)^2 dx$$

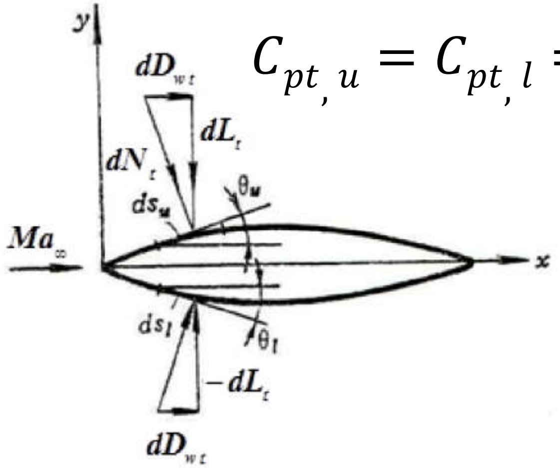


$$ds\sin\theta = dy = dx\left(\frac{dy_f}{dx}\right)$$

$\boxed{\text{弯度产生波阻!}}$

13.7超声速线化理论(10.9)

$$C_{dw\alpha}=\frac{4\alpha^2}{B}\quad C_{dwf}=\frac{4}{cB}\int_0^c\left(\frac{dy_f}{dx}\right)^2dx$$



$$C_{pt,u}=C_{pt,l}=\frac{2}{B}\left(\frac{dy_t}{dx}\right)_u$$

6. C_{dw}: $C_{dw}=C_{dw\alpha}+C_{dwf}+C_{dwt}$

$$C_{dwt}=\frac{1}{c}\int_0^c\frac{4}{B}\left(\frac{dy_t}{dx}\right)ds\sin\theta$$

$$=\frac{1}{c}\int_0^c\frac{4}{B}\left(\frac{dy_t}{dx}\right)\left(\frac{dy_t}{dx}\right)dx$$

$$=\frac{4}{cB}\int_0^c\left(\frac{dy_t}{dx}\right)^2dx$$ 弯度产生波阻!

$$C_{dw}=C_{dw\alpha}+C_{dwf}+C_{dwt}$$

$$\boxed{C_{dw}=\frac{4\alpha^2}{B}+\frac{4}{cB}\int_0^c\left[\left(\frac{dy_f}{dx}\right)^2+\left(\frac{dy_t}{dx}\right)^2\right]dx}=\frac{4}{B}(\alpha^2+g_f^{\,2}+g_t^{\,2})$$

升致波阻
(α引起，与f,t无关)!

零升波阻
(与f,t有关)!

f,t仅产生波阻，不产生升力!

13.7超声速线化理论(10.9)

$$\boxed{C_l = \frac{4\alpha}{B}}$$

$$\boxed{C_{dw} = \frac{4\alpha^2}{B} + \frac{4}{cB}\int_0^c [(\frac{dy_f}{dx})^2 + (\frac{dy_t}{dx})^2] dx}$$

$C_l \propto \alpha$, $C_{dw} \propto \alpha^2$　$\alpha\downarrow$ $C_{dw}\downarrow$　　超声速：小α飞行！

可见：薄翼型的波阻系数由两部分组成，一部分与升力有关，另一部分与弯度和厚度有关。

升致波阻：由迎角引起的波阻，与翼型的形状无关

零升波阻：与升力无关，只与翼剖面有关，特别是与翼型厚度有关。

13.7超声速线化理论(10.9)

7. C_m: ①$C_{m\alpha}$: $\Delta C_{p\alpha}$分布均匀，作用点在$\frac{c}{2}$处

$$C_{m\alpha,0} = -\frac{C_{l\alpha}}{2}$$

②C_{mf}: $C_{mf,0} = \frac{1}{c^2}\int_0^c \frac{4}{B}\left(\frac{dy_f}{dx}\right) dx \cdot x$

$$= \frac{-4}{Bc^2}\left(\int_0^c y_f\,dx - y_f x\Big|_0^c\right)$$

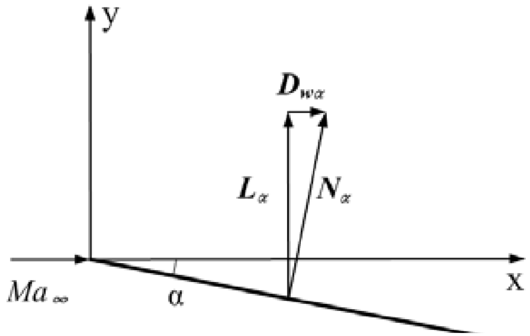
$$= \frac{-4}{Bc^2}\int_0^c y_f\,dx$$

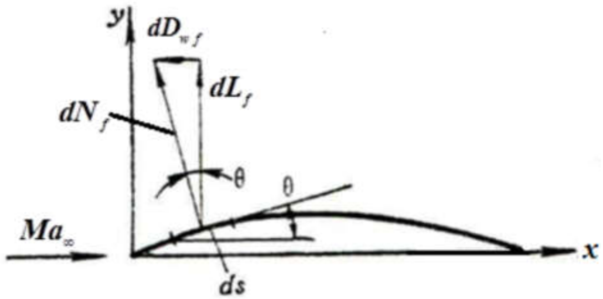
③C_{mt}: $C_{mt}=0$

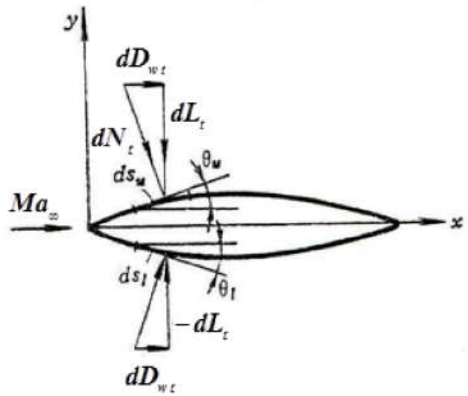
$$C_{m,0} = -\frac{C_l}{2} - \frac{4}{Bc^2}\int_0^c y_f\,dx$$

$$C_{m,0} + \frac{C_l}{2} = -\frac{4}{Bc^2}\int_0^c y_f\,dx$$

与α无关！







13.7超声速线化理论(10.9)

7. C_m:　$C_{m,0} = -\frac{C_l}{2} - \frac{4}{Bc^2}\int_0^c y_f\,dx$

$C_{m,0} + \frac{C_l}{2} = -\frac{4}{Bc^2}\int_0^c y_f\,dx$　　与α无关！

$C_{m,1/2} = C_{m,0} + \frac{C_l}{2} = -\frac{4}{Bc^2}\int_0^c y_f\,dx$　　与α无关！

$\frac{c}{2}$为气动中心！　　$Ma_\infty > 1$气动中心后移！

$Ma_\infty < 1$, $\frac{c}{4}$为气动中心！

13.7超声速线化理论(10.9)

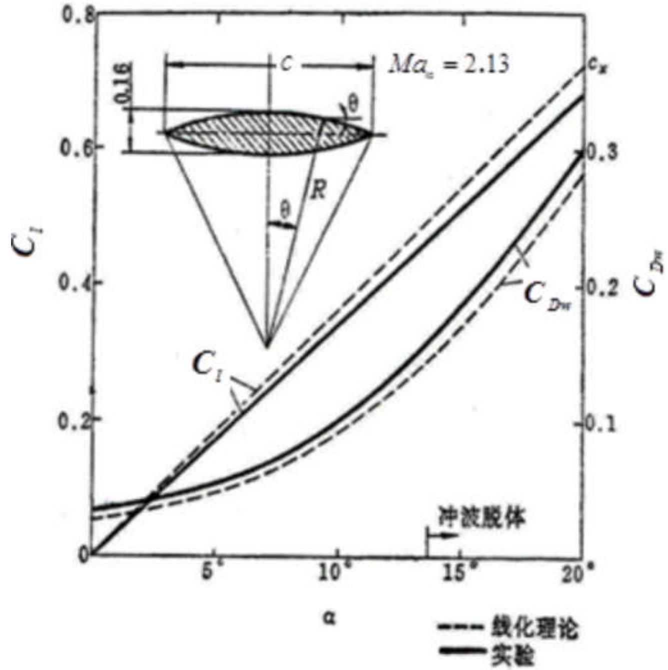
8. 一级线化理论的适用性:

➢ 升力线斜率较实验较高：

线化理论未考虑边界层及其与激波相互干扰。

➢ 波阻较实验较低：

线化理论为无粘阻力，未考虑粘性压差、摩擦阻力。



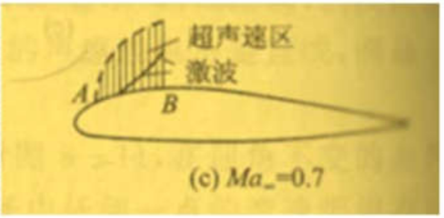
13.8 Ma数对机翼气动特性影响

1. $C_l \sim Ma_\infty$

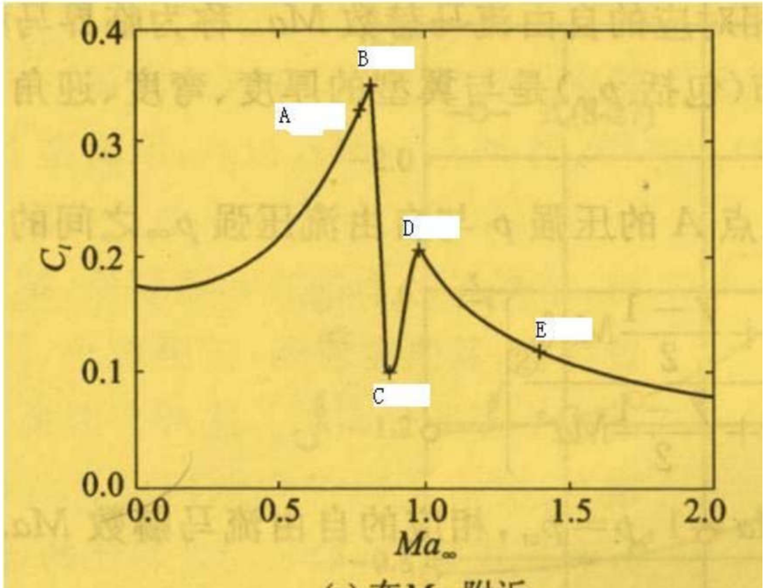
- $Ma_\infty < Ma_{cr}$: $Ma_\infty \uparrow \rightarrow C_l \uparrow$

$$\boxed{\text{亚声速}:C_l = \frac{C_{l0}}{\sqrt{1-Ma_\infty^2}}}$$

- $A-B$: 刚进入跨声速区，
上翼面有超音速区， $C_p \downarrow \rightarrow C_l \uparrow$



(c) Ma_∞=0.7



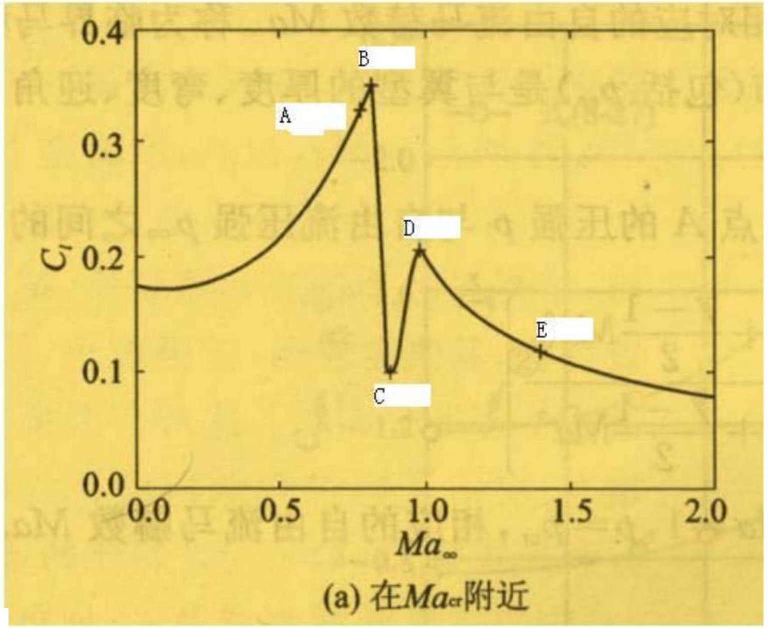
(a) 在Ma_{cr}附近

13.8 Ma数对机翼气动特性影响

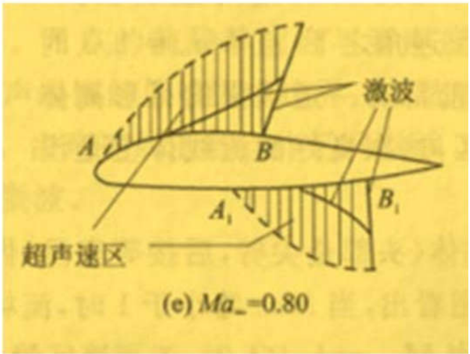
1. $C_l \sim Ma_\infty$

➢ B后: Ma_∞⬆, 上翼面超声速区扩大,
激波后移，强度增大,
波后边界层内逆压梯度剧增
→流动分离，升力C_l⬆骤降！(激波失速)

➢ C前: Ma_∞⬆, 下翼面也出现超声速区,
激波快速移至后缘,
→下翼面压强降低,
→升力C_l⬇ ！



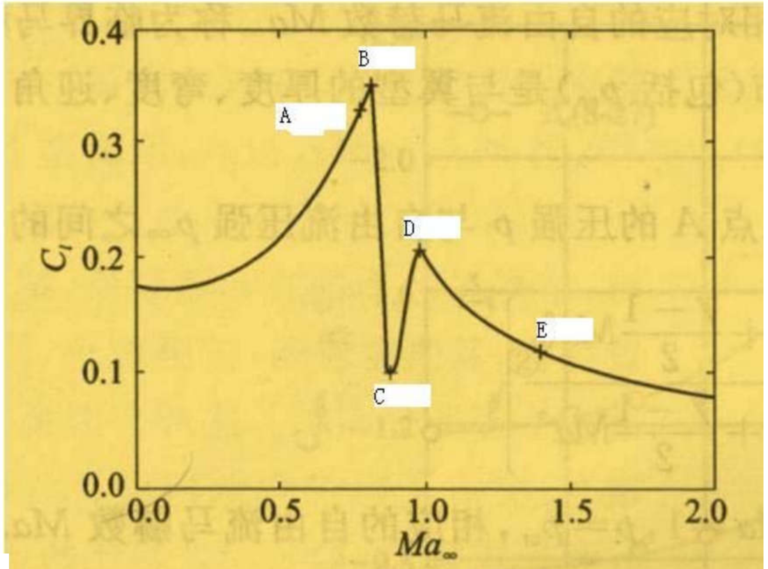
(a) 在Ma_{cr}附近



(e) Ma_∞=0.80

13.8Ma数对机翼气动特性影响

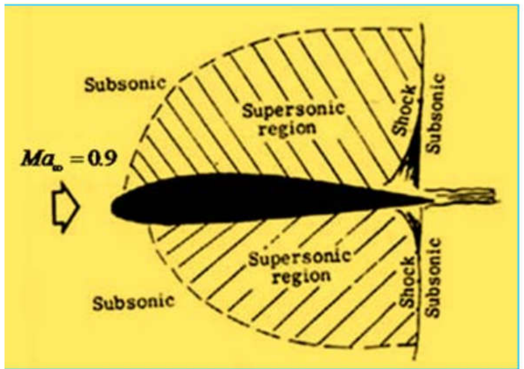
1. $C_l \sim Ma_\infty$



(a) 在Ma_{cr}附近

- $C \sim D$:

Ma_∞⬆, 下翼面超声速区不变,
上翼面激波移至后缘,
上翼面边界层分离点后移
→上翼面C_p⬇ →C_l⬆



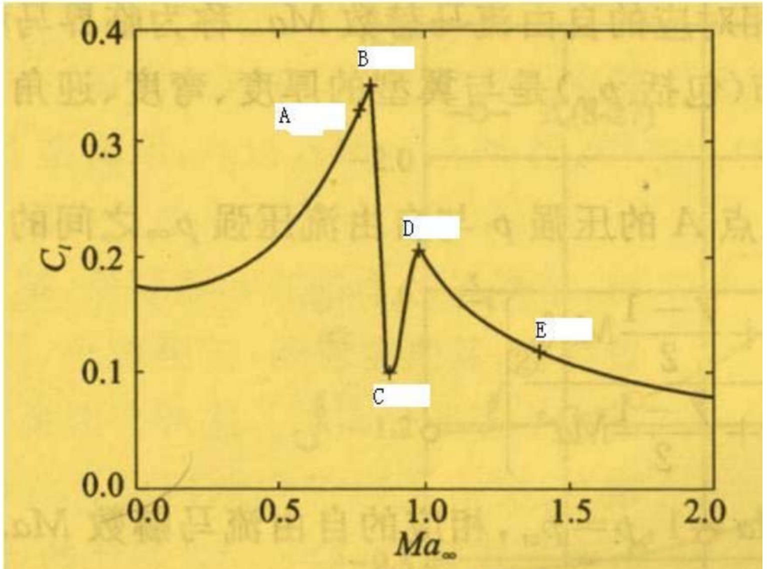
13.8Ma数对机翼气动特性影响

1. $C_l \sim Ma_\infty$

- $D \sim E$: $Ma_\infty > 1$, 翼型超声速绕流，翼型前脱体激波，斜激波
  →Ma_∞↑，C_l↓

$$\boxed{C_l = \frac{4\alpha}{\sqrt{Ma_\infty^2 - 1}}}$$

跨声速飞行中，C_l几上几下，波动大。



(a) 在Ma_{cr}附近

13.8Ma数对机翼气动特性影响

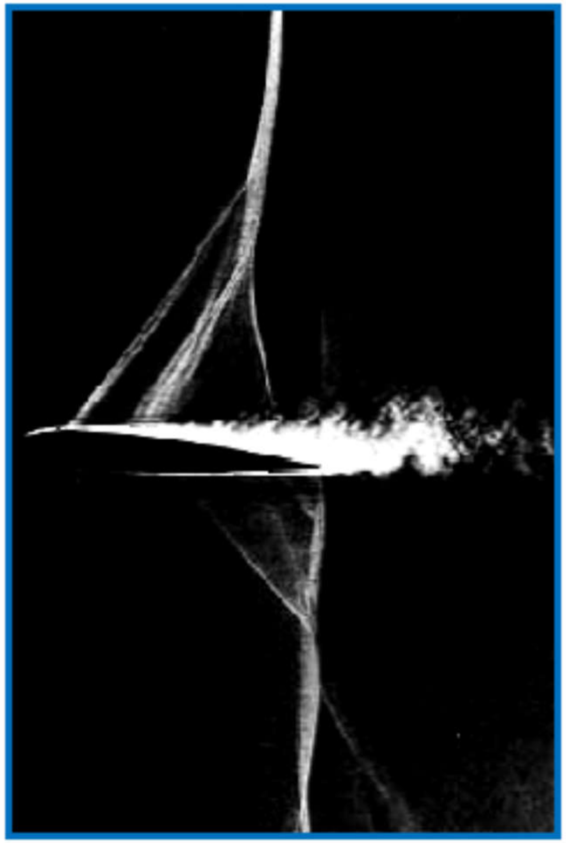
2. λ形激波系 ：

激波→逆压梯度⬆

→边界层厚度⬆

→增厚的边界层使外流形成系列压缩波

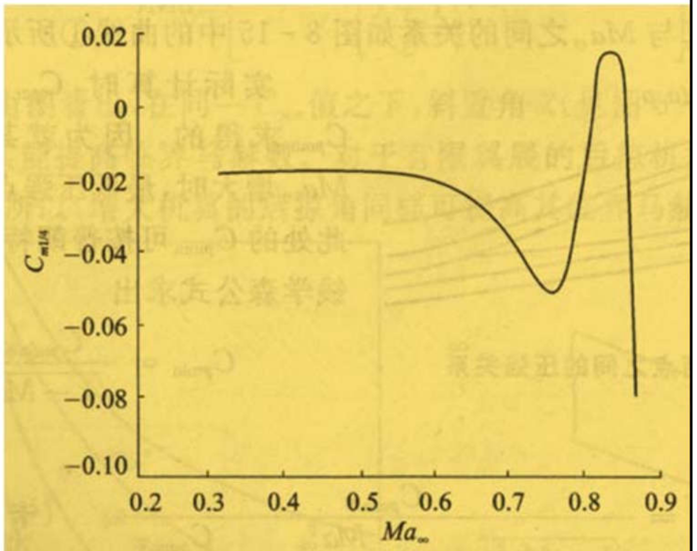
→ λ形激波系



13.8 Ma数对机翼气动特性影响

3. $C_m \sim Ma_\infty$：

跨声速飞行中，纵向力矩变化剧烈，
飞行器操作困难，跨越声障易出事故。



(e) $C_{m1/4} - Ma_\infty$

例：F104战斗机平面面积S=18.21m^2，在11km高空（ρ_∞=0.3648kg/m^3，T_∞=216.78K，R=287J/kgK）以Ma_∞=2飞行。飞机重量为9400kgf。假设飞机重量全由机翼承担，机翼升力系数近似等于翼型升力系数。求飞机机翼的迎角α。

$$C_l = \frac{4\alpha}{\sqrt{Ma_\infty^2-1}}$$

解： **11km高空的当地声速为：**

$$c = \sqrt{\lambda R T_\infty} = \sqrt{1.4\times 287\times 216.78} = 295 m/s$$

飞机飞行速度为：

$$V_\infty = Ma_\infty \cdot c = 2\times 295 = 590 m/s$$

飞机升力为：

$$L = 9400\times 9.8 = 9.212\times 10^4 N$$

机翼升力系数为：

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V_\infty^2\cdot S} = \frac{9.212\times 10^4}{\frac{1}{2}\times 0.3648\times 950^2\times 18.21} = 0.08$$

例：F104战斗机平面面积S=18.21m^2，在11km高空（ρ_∞=0.3648kg/m^3，T_∞=216.78K，R=287J/kgK）以Ma_∞=2飞行。飞机重量为9400kgf。假设飞机重量全由机翼承担，机翼升力系数近似等于翼型升力系数。求飞机机翼的迎角α。

解：翼型升力系数为：$C_l = C_L = 0.08$

超声速翼型升力系数与迎角、来流马赫数的关系为：

$$C_l = \frac{4\alpha}{\sqrt{Ma_\infty{}^2 - 1}}$$

则，机翼的迎角为：

迎角很小，符合小扰动假设。

$$\alpha = \frac{C_l}{4}\sqrt{Ma_\infty{}^2 - 1} = \frac{0.08}{4}\sqrt{2^2 - 1} = 0.035rad = 1.98^\circ$$

作业:

复习笔记!

空气动力学书10.1, 10.2, 10.3