# Chapitre V

# Etude des régimes compressibles en Fluide Parfait

→ Part 1 : Introduction
Description of compressible and inviscid flows
Steady unidirectional compressible flows

→ Part 2 : From pressure waves to shock waves
Normal and oblique shock waves
Examples

*Avertissement : Ce chapitre est tiré du cours de Master donné dans le cadre du « Summer Program » associant les écoles aéronautiques du GEA. Seule la première partie sera traitée.*



*Introduction (1)*

→ Compressibility phenomena are associated with large velocities or large accelerations in a gas flow.

→ The development of this field of fluid mechanics is linked with the evolution of aeronautics in the middle of the 20$^{th}$ century.

→ In fact, it concerns a lot of applications :

$\Rightarrow$ Pneumatic transport

$\Rightarrow$ flows in Intake or exhaust ports of automotive engines

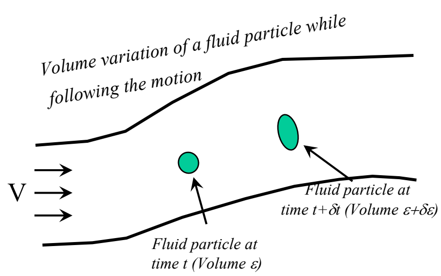
$\Rightarrow$ **……**

## *Description of compressible and inviscid flows (1)*

- Goals :
  - $\Rightarrow$ Physical description
  - $\Rightarrow$ Mathematical model
  - $\Rightarrow$ Definition and properties of stagnation quantities



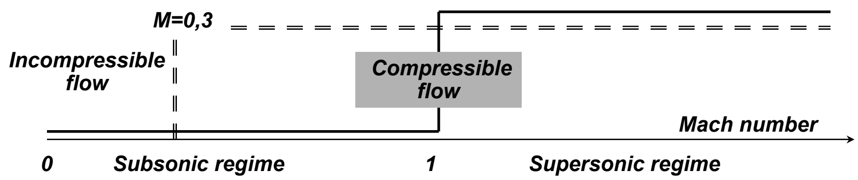
## *Description of compressible and inviscid flows (2)*




- What are the consequences of fluid motion on the variation of the volume of an elementary fluid particle ?
- Important parameter : Mach Number $M = V/a$
- First estimation ( $m = \rho\,\varepsilon$ *constant mass of the fluid particle)*
  - $\left|\dfrac{\delta\varepsilon}{\varepsilon}\right| = \left|\dfrac{\delta\rho}{\rho}\right| = \dfrac{1}{a^2}\left|\dfrac{\delta p}{\rho}\right|$
  - If $\rho \approx$ constant : $\delta p \approx \rho \dfrac{V_\infty^2}{2}$

$$\left|\frac{\delta\varepsilon}{\varepsilon}\right| \approx \frac{M_\infty^2}{2}$$

→ Regimes of compressible flows




***Mach number : M=V/c (c: speed of sound)***

*(For air in standard conditions of temperature and pressure, M=1 corresponds to 330 m/s)*

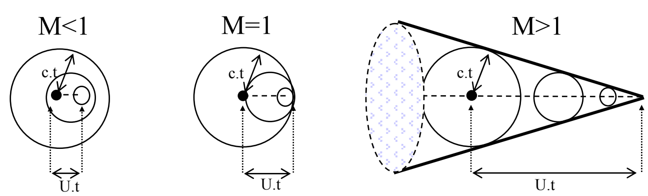
→ In some flows, for example on airfoils, both subsonic and supersonic regions can co-exist. We say that the flow regime is transsonic





→ On both sides of Mach ONE !

→ SOURCE IN MOTION




⇒ Subsonic regime : Information arrives before the source

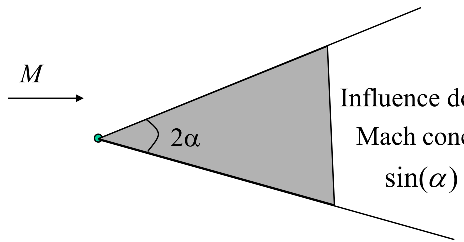
⇒ Supersonic regime : Information arrives after

- Mach cone of angle $\alpha$ / $\sin(\alpha) = 1/M$

⇒ The properties of the equations of motion are changing :
* Subsonic : System elliptic in space
* Supersonic : System hyperbolic in space

## → On both sides of Mach ONE

→ FIXED SOURCE in a Supersonic flow




Influence domain :
Mach cone of angle $2\alpha$
$\sin(\alpha) = 1/M$

$\Rightarrow$ In a supersonic flow, the fluid particle is not "informed" that there is an obstacle !!
- This explains why we observe very sharp transitions
- Explains the apparition of shock waves.





→ Large Reynolds numbers

→ Non buoyant fluid , No volumetric heat transfer

→ We assume that the fluid is a perfect gaz.

* Equation of state : $p/\rho = rT$ where $\mathrm{r} = \mathrm{R}/\mathrm{M}$

* Joule Laws : $de = c_v dT$ ; $dh = c_p dT$

$c_v$ and $c_p$ supposed constant ; $\gamma = c_p / c_v$

Meyer relation : $r = c_p - c_v$

*r is the material specific gaz constant.*
*$c_p$ and $c_v$ are specific heats*
*at constant pressure and volume*

* Entropy : $s = c_v \log\left(p/\rho^\gamma\right)$

* Velocity of sound : $a^2 = \left.\dfrac{\partial p}{\partial \rho}\right|_s = \gamma\, rT = \gamma \dfrac{p}{\rho}$

→ Tables and numerical integration must be used for more complex thermodynamics.

*Mathematical model for compressible and inviscid flows. (2)*

→ Mass, Momentum and energy balance are written .

→ If there are no irreversibilities and no volumetric heat flux,
For a general unsteady flow :

$$\Rightarrow \frac{Ds}{Dt} = 0$$

In a compressible and inviscid flow, the entropy is constant along trajectories.

→ BEWARE : This is only true « pieces by pieces » if there are shock waves.



*Mathematical model for compressible and inviscid flows. (3)*

→ Mass, Momentum and energy balance are written .

→ If there are no irreversibilities and no volumetric heat flux
Case of a permanent flow (which will be considered afterwards)

$$\Rightarrow \vec{V}.g\vec{r}ad(s) = 0$$

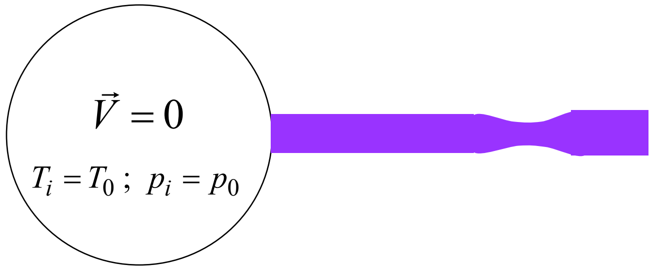
$$\vec{V}.g\vec{r}ad(h_i) = 0 \quad \text{where} \quad h_i = h + \frac{V^2}{2}$$

In a permanent compressible and inviscid flow the entropy and the stagnation enthalpy are constant along streamlines.

→ BEWARE : This is again only true « pieces by pieces » if there are shock waves.

*Permanent regime: practical definitions of the stagnation quantities (1).*

→ Practical point of view : In a tank : $h_i = c_p T_i = c_p T_0$




→ Following theoretical results, along streamlines :

$* \; h_i = h + \dfrac{V^2}{2}$ or $T_i = T + \dfrac{V^2}{2c_p}$ are constant quantities

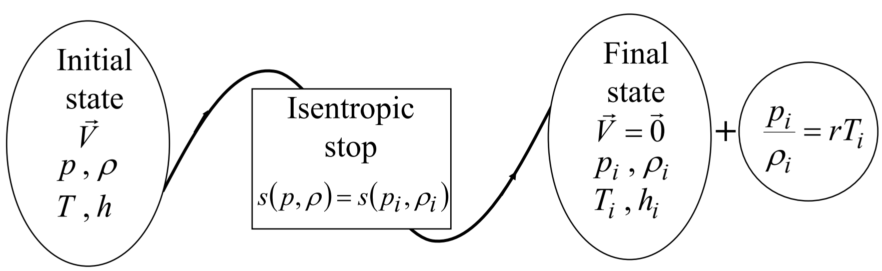
→ If then the properties of the gaz are uniform in the tank :

$\Rightarrow$ $h_i$ et $T_i$ are constant EVERYWHERE.

→ Note that : $h_i = \dfrac{a^2}{(\gamma - 1)} + \dfrac{V^2}{2}$ and $\dfrac{T_i}{T} = \left(1 + \dfrac{(\gamma - 1)}{2} M^2\right)$



*Permanent regime: practical definitions of the stagnation quantities (2).*




→ Following theoretical results, along streamlines :

$*$ $h_i(p_i, \rho_i) = c_p T_i$ AND $s(p_i, \rho_i)$ are independant constant quantities.

$\Rightarrow$ $T_i$ ; $p_i$ et $\rho_i$ are constant quantities along streamlines

→ If then the properties of the gaz are uniform in the tank :

$\Rightarrow$ $T_i$ ; $p_i$ et $\rho_i$ are constant EVERYWHERE.
(Not valid if there are shock waves !!)

→ At a given Mach number M, the ratio between a quantity and the corresponding stagnation quantity are given by :

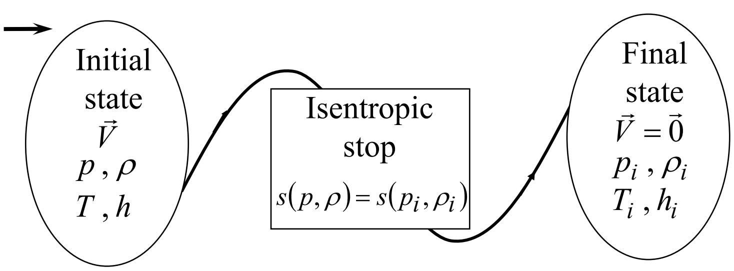
SAINT-VENANT RELATIONS

$$\frac{T}{T_i} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \qquad \frac{p}{p_i} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\gamma/(\gamma-1)}$$

$$\frac{\rho}{\rho_i} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1/(\gamma-1)} \qquad \frac{a}{a_i} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1/2}$$





→ 

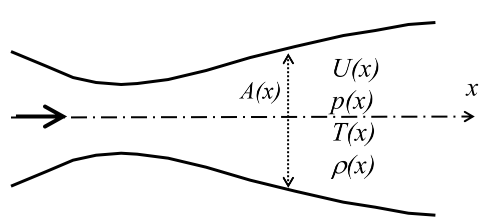

→ In a permanent compressible and inviscid flow
If the boundary conditions are UNIFORM, and if there are NO shock waves :

Initial Conditions + Local Mach number $\Rightarrow$ Local Thermodynamic State of the Gas

Permanent compressible and inviscid
Monodimensional flow
-
Laval Nozzle Flow







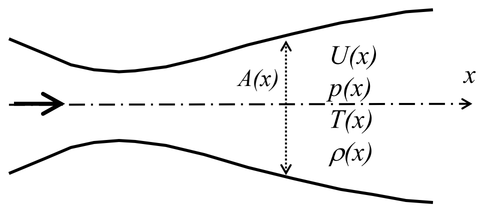

* Quasi-monodimensional flow along the x coordinate

* Slow variations of $A(x)$ with $dA/A << 1$

* Weak curvatures $A/R^2 << 1$

* Uniform boundary conditions

*Permanent compressible and inviscid monodimensional flow: Laval nozzle flow (2)*




* Continuity : $\rho.U.A = cste$

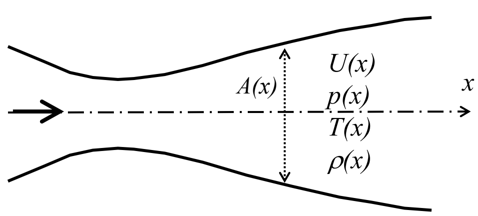
* Momentum : $\rho.U.\frac{dU}{dx} = -\frac{dp}{dx}$

* Enthalpy : $h_i = cste$

* Entropy : $s = cste \Rightarrow \frac{p}{\rho^\gamma} = cste$



*Permanent compressible and inviscid monodimensional flow: Laval nozzle flow (3)*



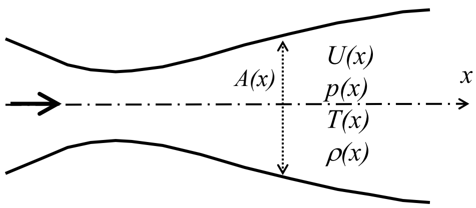

* Continuity : $\frac{d\rho}{\rho} + \frac{dU}{U} + \frac{dA}{A} = 0$

* Momentum : $\rho.U.\frac{dU}{dx} + \frac{dp}{dx} = 0$

* Enthalpy : $h_i = cste$

* Entropy : $\frac{dp}{p} = \gamma \frac{d\rho}{\rho} \Rightarrow dp = a^2 d\rho$

*Permanent compressible and inviscid monodimensional flow: Laval nozzle flow (4)*




Hugoniot Theorem

* Reducing variables :

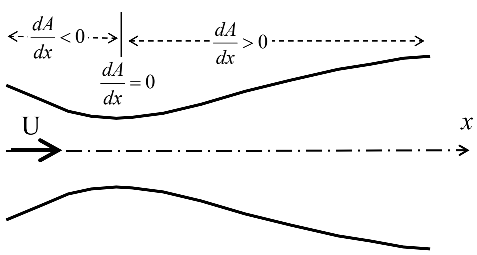
$$\left(M^2-1\right)\frac{dU}{U}=\frac{dA}{A}$$

* In a SUBSONIC FLOW, When section increases, The velocity decreases (and vice versa)

* In a SUPERSONIC FLOW, When section increases, The velocity increases (and vice versa)



*Laval nozzle flow (5)*




At the throat ??

$$\left(M^2-1\right)\frac{dU}{U}=\frac{dA}{A}$$

* If M=1 , then dA=0

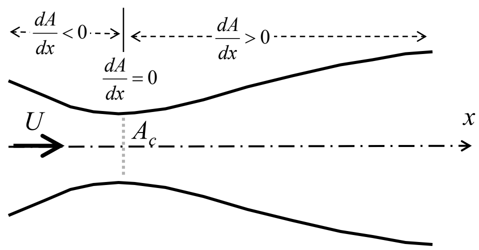
If an isentropic monodimensional flow is sonic, then we are at a minimum of the cross-section.

* Conversely, if dA=0 :

⇒ Either dU=0

⇒ Either M=1. In this case, we are at a MINIMUM of the section

*Laval nozzle flow(6)*




$M = M_c = 1$
at $A = A_c$

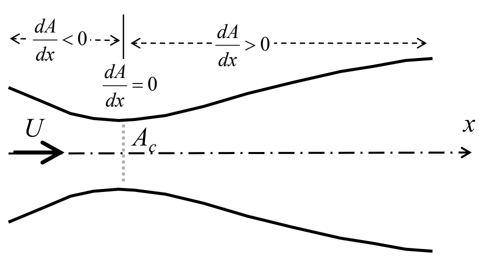
* With a sonic flow at the throat, we obtain for the mass flux :

$$\Rightarrow \qquad Q_m = \sqrt{\frac{\gamma}{r}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{p_i}{\sqrt{T_i}} A_c = \left(4.04.10^{-2}\right)\frac{A_c\, p_i}{\sqrt{T_i}} \qquad (\gamma = 1.4)$$

* This relation has a lot of practical applications if one wants to regulate a mass flux just by controlling the initial stagnation pressure $p_i$



*Laval nozzle flow (7)*




$$\left(M^2 - 1\right)\frac{dU}{U} = \frac{dA}{A}$$

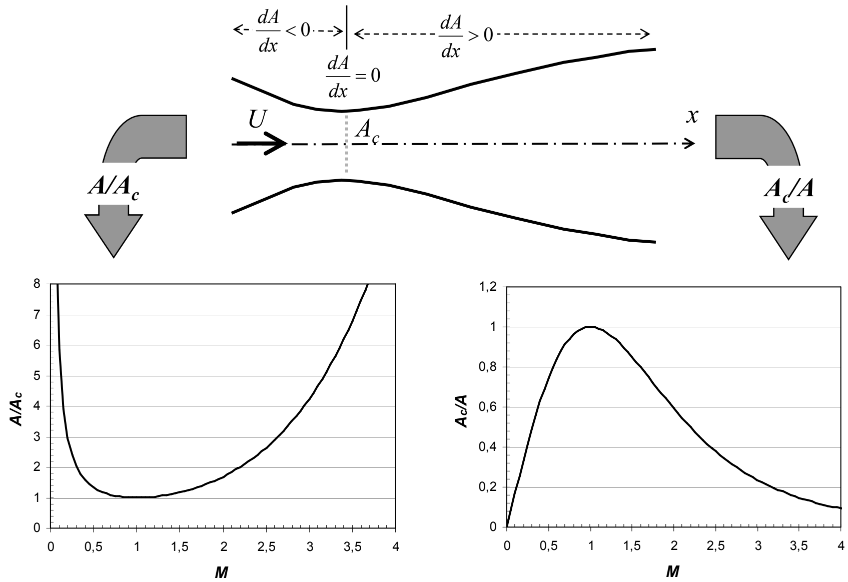
* By definition, the throat conditions are defined by :

$M = M_c = 1$ at $A = A_c$ *(This section can be virtual !!)*

* An important theoretical link between $A/A_c$ and the local Mach number is :

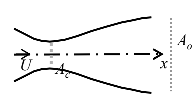
$$\Rightarrow \qquad \frac{A}{A_c} = \frac{1}{M}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

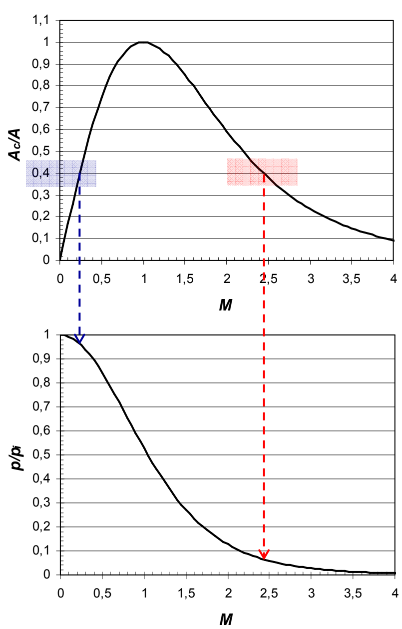
## *Laval nozzle flow (7)*






## *Laval nozzle flow (8)*




* Applications :

- Atmospheric conditions at entrance
- Varying outlet pressure
- Outlet section : $A_o / A_c = 2.5$

* Subsonic flow and $M = 1$ at the minimum section. $M_o$ , $p_o$ ???

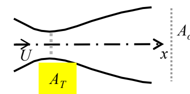
$\Rightarrow M_o = 0.24$ and $p_o / p_i = 0.96$

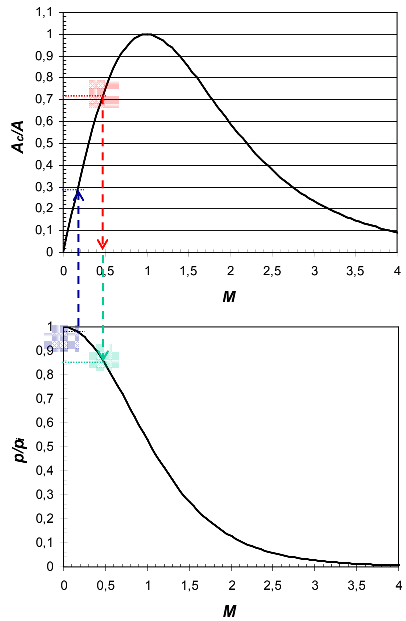
* Supersonic flow and M=1 at the minimum section. $M_o$ , $p_o$ ???

$\Rightarrow M_o = 2.44$ and $p_o / p_i = 0.064$

AND FOR OTHER VALUES OF $p_o / p_i$ ???

## *Laval nozzle flow (9)*




* Conditions :

- Atmospheric conditions at entrance
- Varying outlet pressure
- Outlet section : $A_o / A_T = 2.5$

* $p_o / p_i = 0.98$

value of $M_o, M_s$ ???

$\Rightarrow M_o = 0.17$

$\Rightarrow A_c / A_o = 0.29$ * $A_o / A_T = 2.5$

$\Rightarrow A_c / A_T = 0.72$

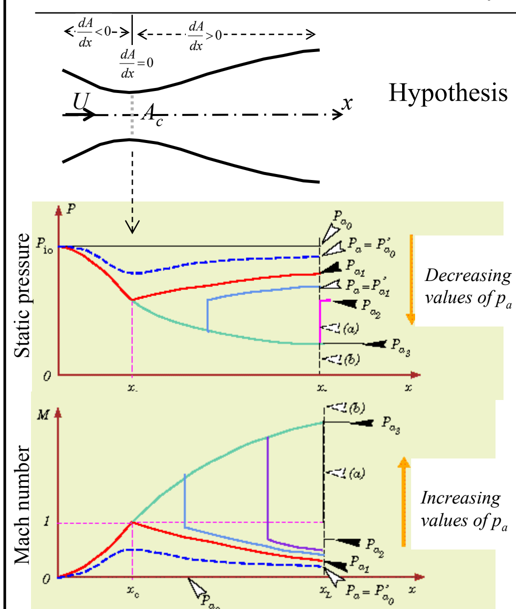
$\Rightarrow M_T = 0.48$

$\Rightarrow p_T / p_i = 0.854$

*The section "C" is here virtual.*



## *Laval nozzle flow (10)*




*(From Chassaing 1997)*

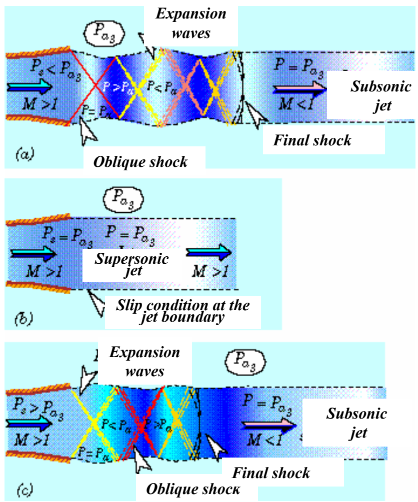
Hypothesis : Fixed upstream stagnation pressure
$p_o$ : Decreasing static pressure at outlet

* For : $p_{a1} < p_o$
- Isentropic subsonic flow

* For : $p_s = p_{a1}$
- Isentropic flow
*M=1* at the throat

* For : $p_{a2} < p_s < p_{a1}$
- NON isentropic flow
- Formation of straight shock waves in the diverging section

*Laval nozzle flow (11)*




* For : $p_{a3} < p_s < p_{a2}$
- Compression at the oulet by oblique shock waves

* For : $p_s = p_{a3}$
- Isentropic Supersonic flow

* For : $p_s < p_{a3}$
- Expansion wave at the outlet reflecting on the boundary of the jet *(p is a constant on this surface)*

*(From Chassaing 1997)*



*Synthesis of this first part*

→ Presentation of the mathematical model for compressible inviscid flows

→ Presentation of physical properties of monodimensional and isentropic compressible inviscid flows

→ The appearance of shock waves has been evidenced

→ In the next part :
* We explain what is a shock wave
* We give some examples

→ Sound wave : A very small perturbation of the pressure field

Examples of levels acceptable for a human ear *($p_0$=1 atm)*:

* $p'/p_0 \in \left[10^{-9}, 10^{-5}\right]$
* Corresponds to $u'/a_0$ et $\rho'/\rho_0$ of the same order

→ Shock wave: finite amplitude jump

* Irreversibility
* The sound wave is a limiting case for asymptotically small pressure jumps.





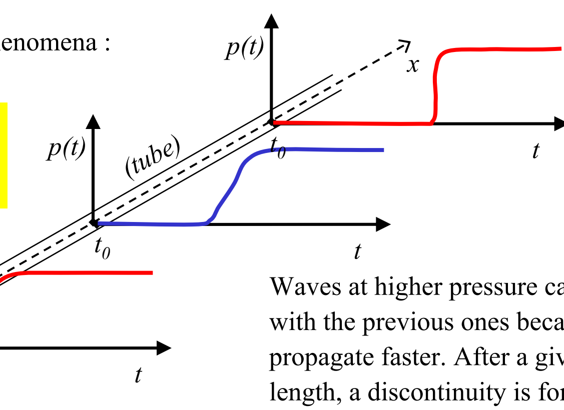
→ Shock waves are discontinuities. Why ?

*Let's imagine that we increase the pressure level at a given location in a tube.*

For isentropic phenomena :

$a^2 \approx p^{(\gamma-1)/\gamma}$

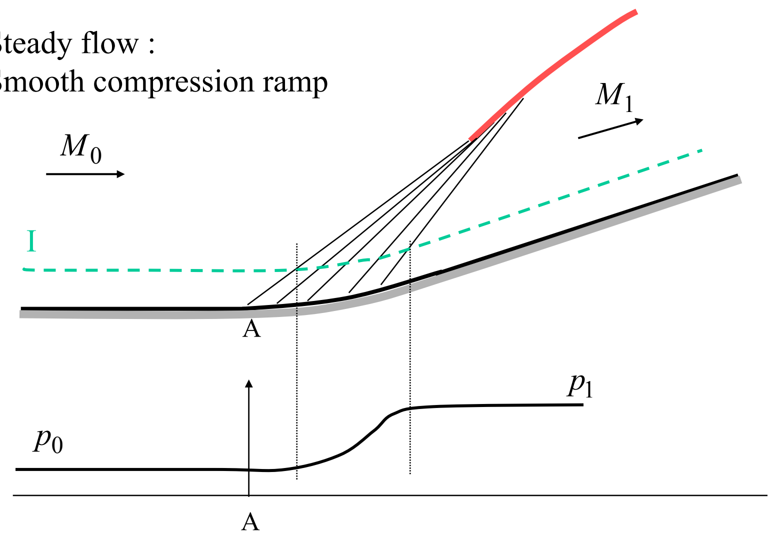
⇒ The speed of sound increases with pressure




Waves at higher pressure catch up with the previous ones because they propagate faster. After a given tube length, a discontinuity is formed.

→ *On the contrary, a smoothing of the pressure evolution occurs during an expansion.*

→ Steady flow :
Smooth compression ramp

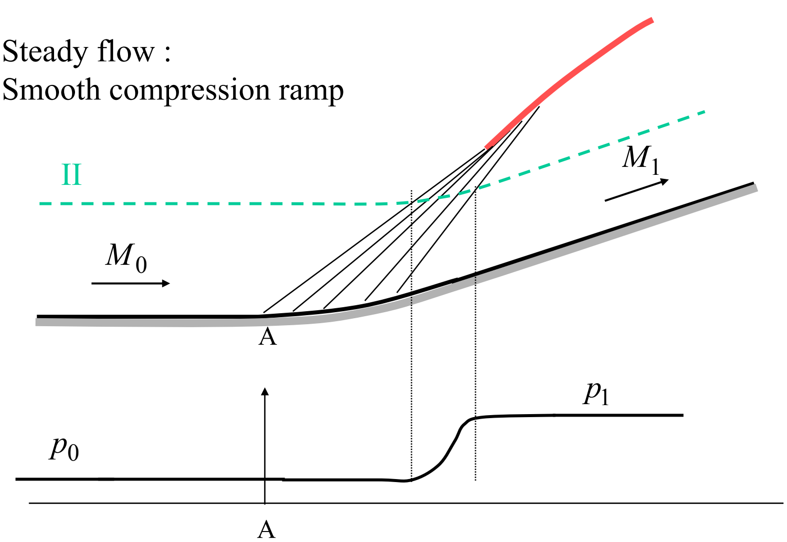



→ Evolution of the pressure along trajectory I



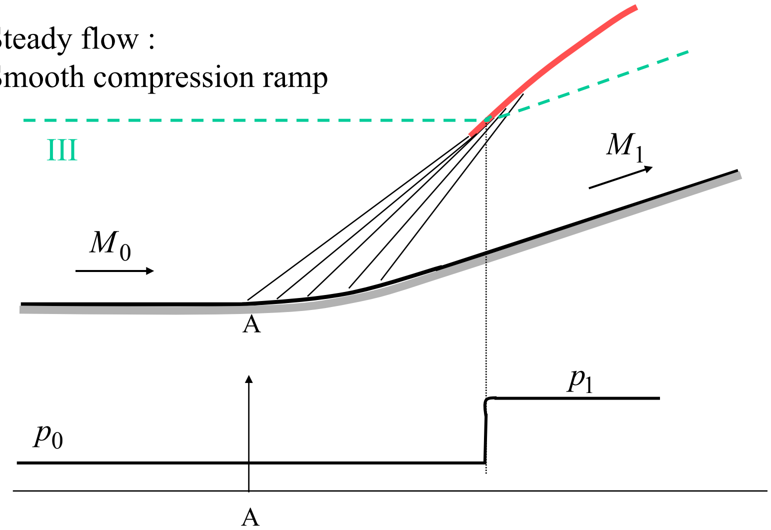


→ Steady flow :
Smooth compression ramp




→ Evolution of the pressure along trajectory II

→ Steady flow :
Smooth compression ramp

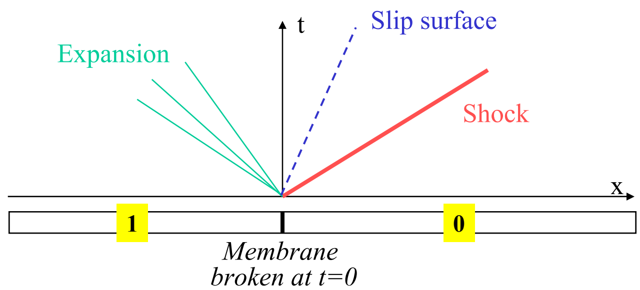



→ Evolution of the pressure along trajectory III

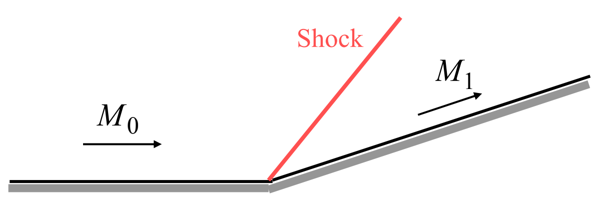


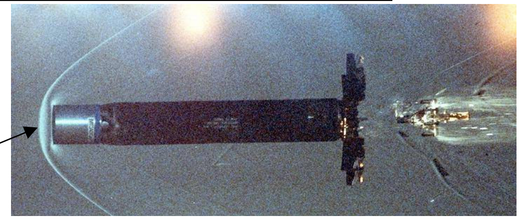


→ Unsteady regime : Shock tube $p_1 > p_0$

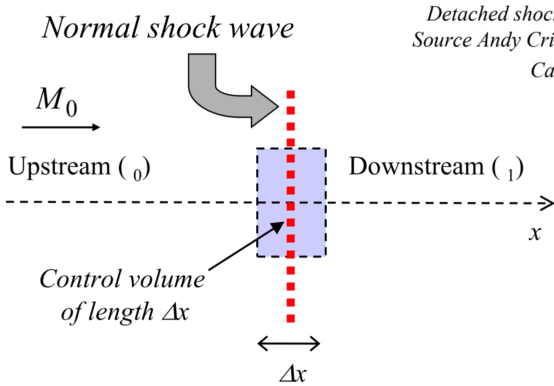



→ Steady regime : Sudden deviation of the wall



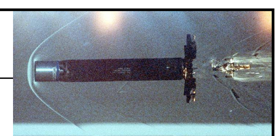


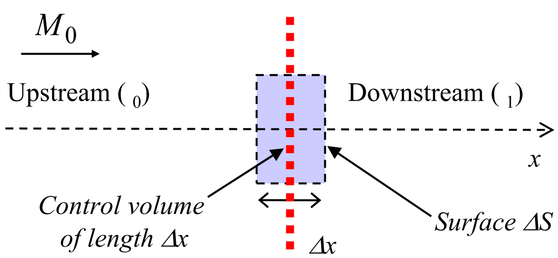
*Detached shock generated by a very blunt projectile.*
*Source Andy Crickenberger Gallery of Fluid Mechanics*
*Cambridge University Press*







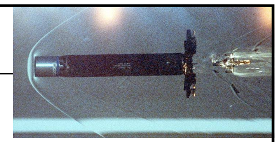



* If $\Delta x \rightarrow 0$ , balances are used to link fluxes through ΔS

- Mass : $\rho_0 U_0 = \rho_1 U_1$
- Momentum : $p_0 + \rho_0 {U_0}^2 = p_1 + \rho_1 {U_1}^2$
- Enthalpy : $h_0 + \frac{{U_0}^2}{2} = h_1 + \frac{{U_1}^2}{2}$

• In steady flows : $h_i$ (and then $T_i$ ) are constant across the shock wave. *Natural consequence of first principle in thermodynamics.*

*Normal shock waves*



* Static pressure and density jumps are only dependant on the upstream Mach number : *(After a tedious work with equations !)*

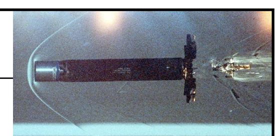
$$\frac{p_1}{p_0} = 1 + \frac{2\gamma}{\gamma+1}\left(M_0{}^2 - 1\right) \quad \text{and} \quad \frac{\rho_1}{\rho_0} = \frac{(\gamma+1)M_0{}^2}{(\gamma-1)M_0{}^2 + 2}$$

* After eliminating $M_0$, we obtain an important relation due to Hugoniot :

$$\frac{\rho_1}{\rho_0} = \frac{1 + \dfrac{\gamma+1}{\gamma-1}\dfrac{p_1}{p_0}}{\dfrac{\gamma+1}{\gamma-1} + \dfrac{p_1}{p_0}} \quad \text{or} \quad \left(\frac{\rho_1}{\rho_0} - 1\right) = \frac{2}{\gamma-1}\,\frac{\left(\dfrac{p_1}{p_0} - 1\right)}{\dfrac{\gamma+1}{\gamma-1} + \dfrac{p_1}{p_0}}$$



*Normal shock waves*



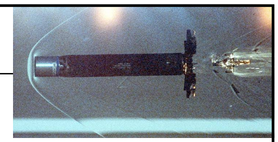
* What means Hugoniot relation for $p_1/p_0 \approx 1$ ???

$$p_1/p_0 = 1 + \varepsilon \quad (\varepsilon << 1) \quad \Rightarrow \quad \left(\frac{\rho_1}{\rho_0} - 1\right) \approx \frac{2}{\gamma-1}\,\frac{(\varepsilon)}{\dfrac{\gamma+1}{\gamma-1} + 1} \approx \frac{1}{\gamma}\left(\frac{p_1}{p_0} - 1\right)$$

$$\Rightarrow \quad Log\left(\frac{\rho_1}{\rho_0}\right) \approx \frac{1}{\gamma}\, Log\left(\frac{p_1}{p_0}\right) \quad \text{ou} \quad \left(\frac{p_1}{\rho_1{}^\gamma}\right) \approx \left(\frac{p_0}{\rho_0{}^\gamma}\right)$$

* For an asymptotically weak shock wave, we thus tend toward an isentropic evolution

* In the general case, the evolution through the shock wave IS NOT isentropic. Irreversibility occurs.



* Second principle of thermodynamics

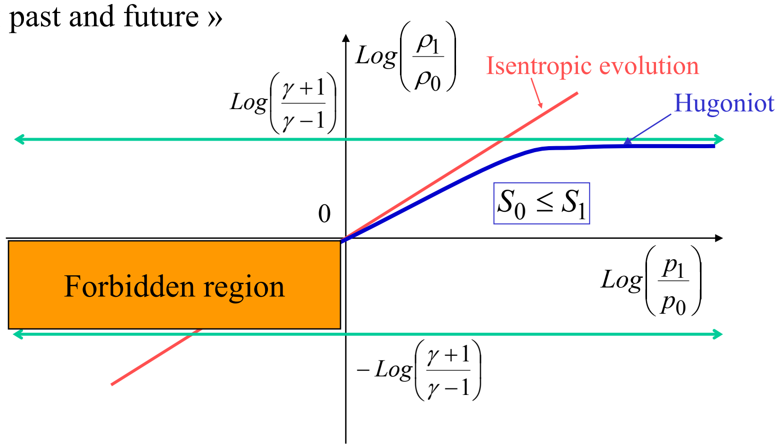
$$S_0 \le S_1 \Leftrightarrow Log\left(\frac{p_0}{\rho_0{}^{\gamma}}\right) \le Log\left(\frac{p_1}{\rho_1{}^{\gamma}}\right) \Leftrightarrow Log\left(\frac{\rho_1}{\rho_0}\right) \le \frac{1}{\gamma} Log\left(\frac{p_1}{p_0}\right)$$

* Knowing that $p_1/p_0 \in [0,+\infty[$ , we just compare the evolution of the pressure obtained by Hugoniot to an isentropic evolution.



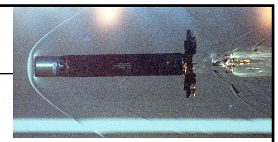


* The second principle enables to distinguish « past and future »




* Thus $S_0 \le S_1 \Rightarrow \underline{p_1/p_0 \ge 1 \text{ et } \rho_1/\rho_0 \ge 1}$

*Normal shock waves*



* Evolution of the Mach number :

Upstream : $$\frac{p_1}{p_0} - 1 = \frac{2\gamma}{\gamma+1}\left(M_0^{\,2} - 1\right) \Rightarrow \underline{M_0^{\,2} \geq 1}$$

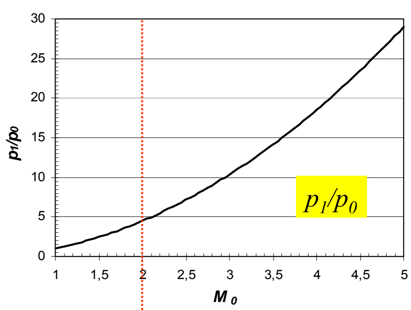
Downstream : $$M_1^{\,2} - 1 = (\gamma+1)\,\frac{\left(1 - M_0^{\,2}\right)}{2\gamma\, M_0^{\,2} - (\gamma - 1)} \Rightarrow \underline{M_1^{\,2} \leq 1}$$

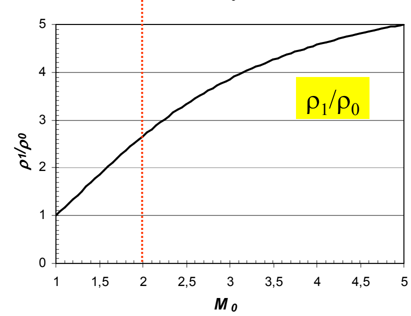
* If a normal shock wave is found in a steady flow, then :

- The upstream Mach number is greater than one (the flow has to be supersonic !)
- The downstream Mach number is lower than one.



*Normal shock waves*

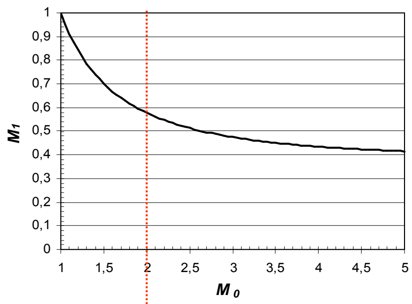


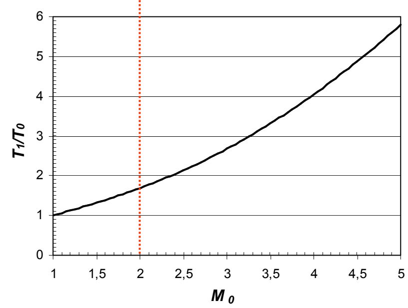




- The pressure and density jumps accross a normal shock wave are large.

- For example :

  - $M_0=2$ implies $p_1/p_0= 4.5$ and $\rho_1/\rho_0=2.67$
  - As a comparison, we remind that a sound wave of rms fluctuating pressure level of 2 Pa (2 $10^{-5}$ bar) corresponds to 100 dB and that pain occurs at 120 dB (20 Pa rms)




- Decrease of the Mach number and increase of the static temperature.

- For example :

  -$M_0=2$ implies
  $T_1/T_0= 1.69$ and $M_1=0.58$

What about stagnation quantities ??





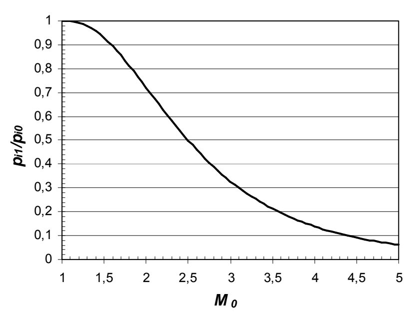
* For steady flow : $h_i$ (and thus $T_i$) remain constant across the shock.

* After a little algebra, one finds : $S_1 - S_0 = c_v(1-\gamma)Log\left(\frac{p_{i1}}{p_{i0}}\right)$

$$\Rightarrow \frac{p_{i1}}{p_{i0}} \leq 1 \text{ et } \frac{\rho_{i1}}{\rho_{i0}} \leq 1$$

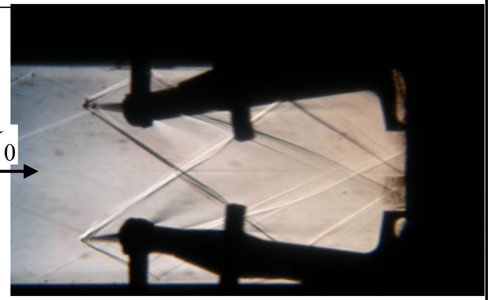
* The stagnation pressure decreases across the shock

* The shock induces logically a loss due to dissipative phenomena.

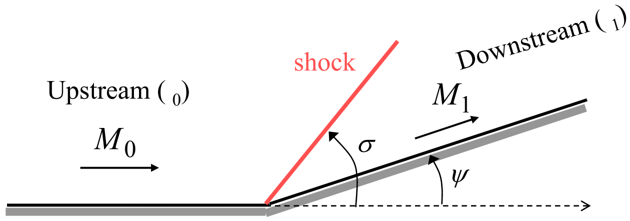



Example : $M_0=2$ implies $p_{i1}/p_{i0}= 0.72$

*Oblique shock wave*

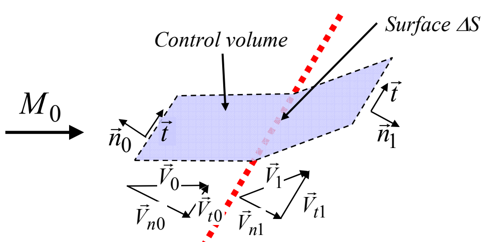


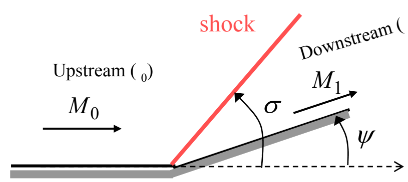

*Oblique shock waves generated by two "knifes" arranged in a symmetrical way in a supersonic wind tunnel at ENSMA. Courtesy of E. Collin.*







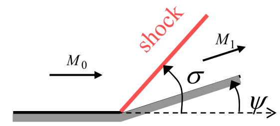




* Flux relations across $\Delta S$

- Mass : $\rho_0 U_{n0} = \rho_1 U_{n1}$
- Momentum / $\vec{n}$ : $p_0 + \rho_0 {U_{n0}}^2 = p_1 + \rho_1 {U_{n1}}^2$
- Momentum / $\vec{t}$ : $U_{t0} = U_{t1}$
- Enthalpy: $h_0 + \frac{1}{2}\left({U_{t0}}^2 + {U_{n0}}^2\right) = h_1 + \frac{1}{2}\left({U_{t1}}^2 + {U_{n1}}^2\right)$

* In steady flow, $h_i$ (and $T_i$) are constant across the shock wave

## *Oblique shock waves*




* By eliminating $U_{t0} = U_{t1}$ in the enthalpy equation :
  - Mass : $\rho_0 U_{n0} = \rho_1 U_{n1}$
  - Momentum / $\vec{n}$ : $p_0 + \rho_0 {U_{n0}}^2 = p_1 + \rho_1 {U_{n1}}^2$
  - Enthalpy : $h_0 + \frac{1}{2}{U_{n0}}^2 = h_1 + \frac{1}{2}{U_{n1}}^2$

* These are STRICTLY the same equations than the one found for normal shock waves.

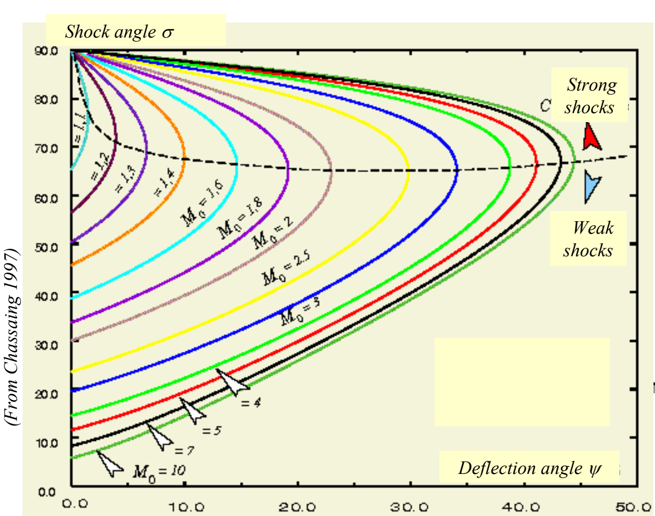
* Jump relations are therefore EXACTLY THE SAME if written here as a function of $M_{n0} = U_{n0}/a_0$ *(see slides 43 and 44)*

* In particular, the steady oblique shock wave exists if : $M_{n0} = M_0 \sin(\varepsilon) > 1$

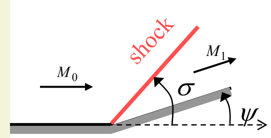


## *Oblique shock waves : about angles*

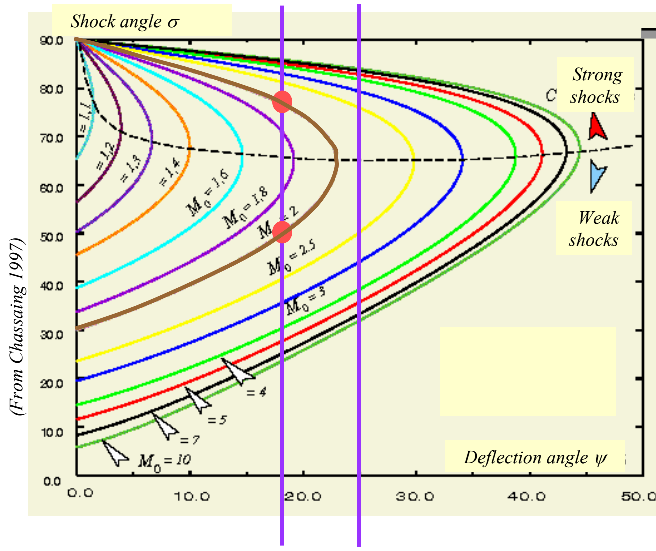
** Mass balance + jump relation $\rho_1/\rho_0$* $\Rightarrow$ $\dfrac{tg(\sigma-\psi)}{tg(\sigma)} = \dfrac{2}{(\gamma+1){M_0}^2 \sin^2(\sigma)} + \dfrac{(\gamma-1)}{(\gamma+1)}$

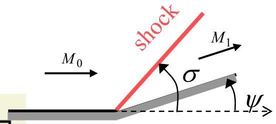



*(From Chassaing 1997)*



## *Oblique shock waves : about angles*



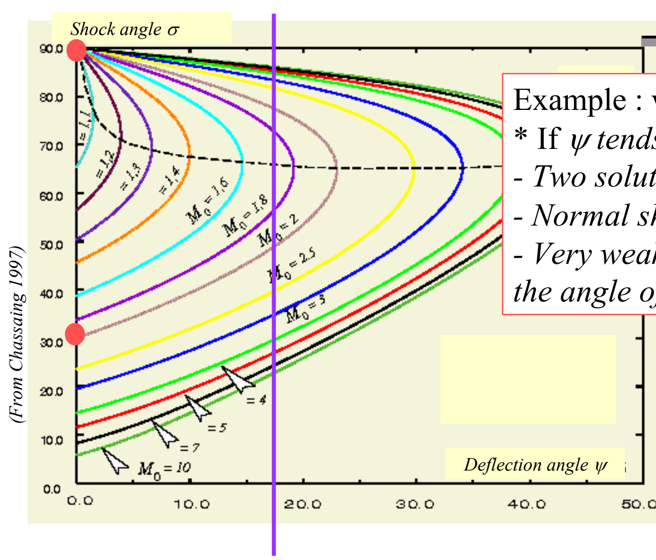

Example : $M_0=2$

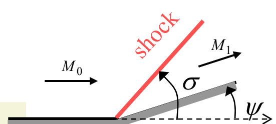
* If $\psi < 23°$
- *Two solutions*
- *Choose the weak shock solution because $M_1>1$*

* If $\psi > 23°$
- *NO solution*
- *The shock is then detached*



## *Oblique shock waves : about angles*

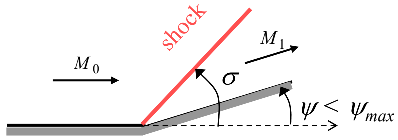


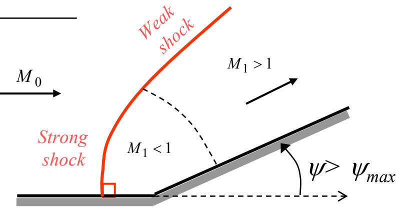

Example : whatever $M_0$

* If *$\psi$ tends toward 0°*
- *Two solutions*
- *Normal shock with $\sigma$=90°*
- *Very weak shock, $\sigma$ being the angle of the Mach cone !*

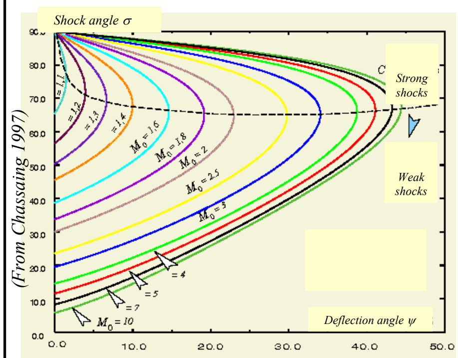
## *Oblique shock waves : about angles*




*Attached shock wave : analytical solution*



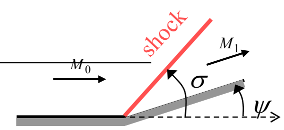

*Detached shock wave : NO analytical solution*




Detached shock waves are complex.
- *The shock has to be normal along the wall (no deviation of the stream line)*
- *Therefore, there is a subsonic region and information can move upstream the corner.*
- *The shock is curved and the downstream region is NOT uniform.*



## *Oblique shock waves : An example of computation*




* Algorithm :

If $M_0$ and $\psi$ are known :

$M_0 ; \psi$

Attached ??

NO | YES

$\sigma$

$M_{n0} = M_0 \sin\sigma$

$p_1/p_0 ; \rho_1/\rho_0$

$M_{n1}$

$M_1$

* Example : $M_0 = 2$ and $\psi = 15°$:

$M_0 ; \psi$

Attached ??

YES

$\sigma = 45°$

$M_{n0} = 1.41$

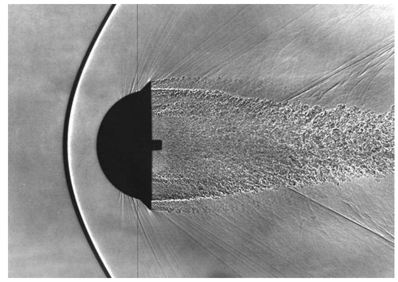
$p_1/p_0 = 2.15$

$M_{n1} = 0.74$

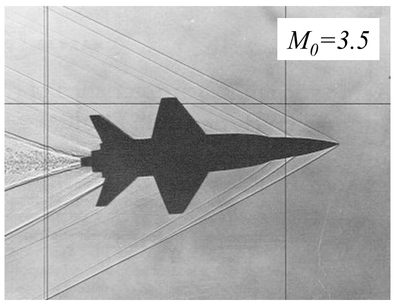
$M_1 = M_{n1} / \sin(\sigma - \psi) = 1.48$

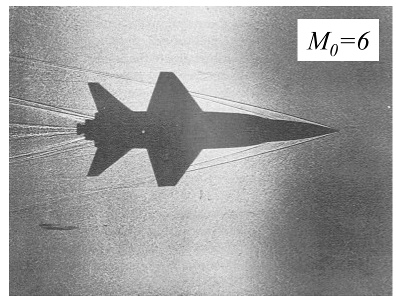
*Shock waves : Some examples*

**Blunt Body**
**Shock Waves**
***(Source NASA)***



* Free supersonic flight of an X15 model in the 50’s and 60’s !




*Conclusions*

→ Shock waves result from the progressive or rapid focussing of pressure waves.

→ Shock waves are associated with large jumps in pressure, density, … and are dissipative phenomena..

→ Normal or oblique shocks can be simply computed using tables.

→ Detached shock waves are complex. Numerical simulations are needed.

→ These basic informations can be completed by the study of :

* Expansion and compression waves using the method of characteristics for 2D or axisymetric steady supersonic flows

* Monodimensional unsteady compressible flows

* …