Supersonic-mode transition in a dense-gas boundary layer at Mach 6

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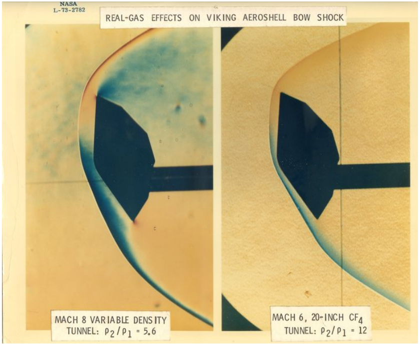
Scope of the present study

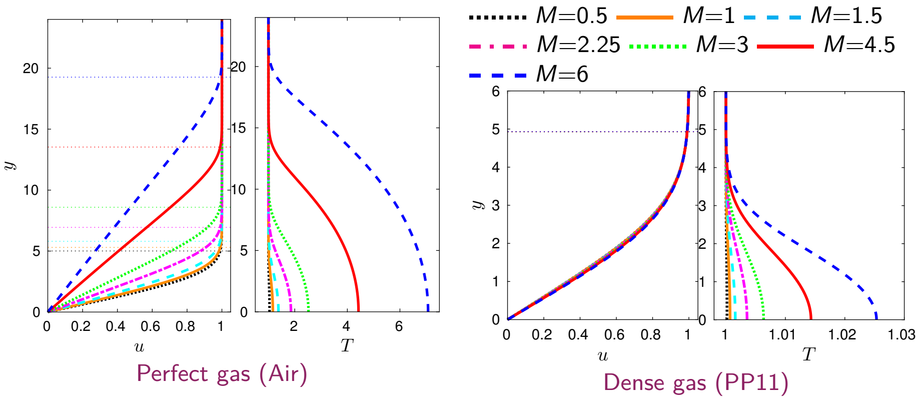
- Study of non-ideal gas effects on boundary layer (BL) transition
- Previous stability analysis[1]: very different results for dense gases at high-speeds → **supersonic mode**
- The challenge is then to determine if this peculiar mode can eventually lead to transition toward a turbulent state
- First investigation of supersonic-mode breakdown for perfluorocarbon PP11 (numerical dense-gas wind tunnel)



high-Mach, high-Reynolds NASA Langley **CF4 wind tunnel**, dismantled in 2017, which used a light perfluorocarbon, CF_4

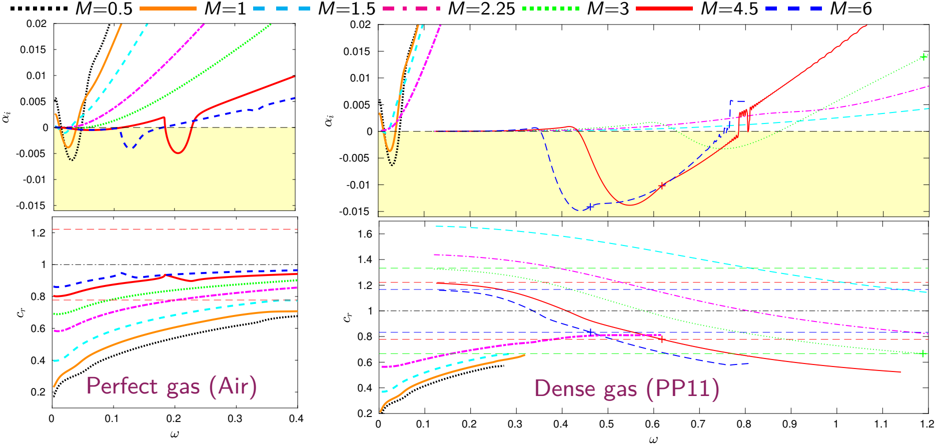
[1] stability: Gloerfelt, Robinet, Sciacovelli, Cinnella & Grasso, "Dense gas effects on compressible boundary layer stability", J. Fluid Mech., 893:A–19–1–41, 2020

[2] turbulent regime & numerical details: Sciacovelli, Gloerfelt, Passiatore, Cinnella & Grasso, "Numerical investigation of high-speed turbulent boundary layers of dense gases", Flow Turb. Combust., 105:555-579, 2020



- Dense gas: high C_p → very small T variations → almost no friction heating → BL thickening close to incompressible regime
- robust w.r.t. fluid (PP11; R134a; R245fa; MDM; D_6) and operating conditions ($\Gamma_\infty < 0$; $\Gamma_\infty < 1$; $\Gamma_\infty > 1$; dilute gas)

Laminar boundary layer: Stability results



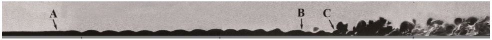
Very different results for $M > 1$!!

- Perfect gas: **first mode** weakened but unstable and 3D (oblique mode) and **second mode** (2D) dominates for $M > 4$.
- Dense gas: first mode stable for $M > 2$; no second mode from Slow-mode-branch; appearence of a **supersonic mode** (2D) from Fast-mode-branch at high frequencies

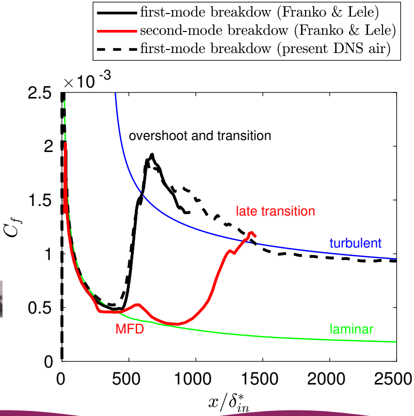
Modal scenarii for perfect gas

- Modal (natural, controlled) transition:
  - incompressible Tollmien-Schlichting (TS): viscous instability
  - for supersonic flows, TS more unstable in 3D (oblique waves) but weakened by compressibility
  - for $M \gtrsim 3$ first mode (extension of TS) becomes an inviscid instability
  - for $M \gtrsim 4$, second mode (2D acoustic mode) is the most unstable but first mode can be still present
- two scenarii for hypersonic boundary layers: **first-mode oblique** or **second-mode breakdown**

  Franko & Lele, J. Fluid Mech (2013)
- second mode is excited in experiments but the route to turbulence is unclear (*e.g.* Fasel's team, expe Zhang et al. ↓)



- first mode can be more efficient → (lower frequency)

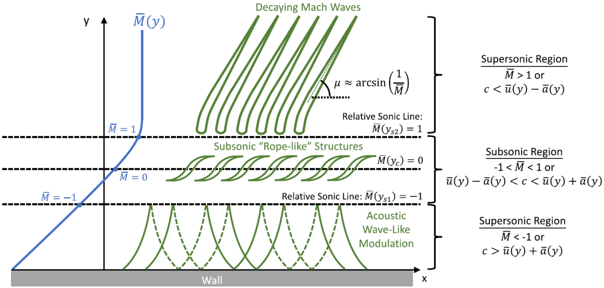


Modal scenarii for dense gas

The only unstable mode for $M \gtrapprox 2.5$ is the supersonic mode
(the inviscid first mode is not present due to the absence of a generalized inflection point)

- predicted in air for high-enthalpy hypersonic boundary layers with strong wall cooling

  BUT only linear wavepacket (no nonlinear transition to turbulence $\rightarrow$ open question)



Knisely & Zhong, Phys. Fluids (2019a,b)

Bitter & Sheperd, J. Fluid Mech (2013)

- pertains to acoustic mode

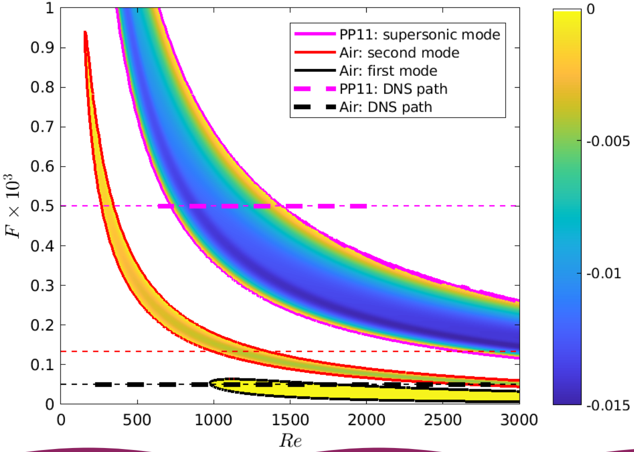
  smaller BL thickening $\rightarrow$ smaller acoustic waveguide height $\rightarrow$ high frequency

  most unstable in 2D and high amplification rate

DNS simulations: parameters of M=6 BL

	U_∞ [m/s]	ρ_∞ [kg/m^3]	T_∞ [K]	T_w [K]	Ec$_\infty$	Re$_\theta$	δ_{99} [mm]	θ [mm]	H
Air†	969.7	0.13	65	422.5	14.4	5720	5.98	0.23	13.81
PP11	198.8	348.4	646.83	663.2	0.0033	4402	0.032	0.0031	2.12

† same parameters as Franko & Lele, J. Fluid Mech (2013)



DNS simulations: code

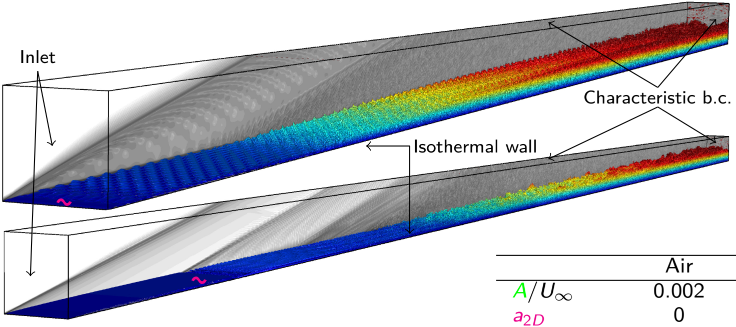
Flow governed by the 3D compressible Navier–Stokes equations

Code MUSICA2

- 10th-order standard centered scheme for inviscid fluxes
- 9th-order Jameson-type non-linear artificial viscosity + Ducros sensor
- 4th-order standard centered scheme for viscous fluxes
- Explicit four-step low-storage Runge-Kutta for time integration
- Equation of state: Ideal gas for air and Martin-Hou virial law for PP11
- Transport properties: Sutherland+cst Prandtl for air and Chun-Lee-Starling for PP11
- Characteristic boundary conditions (+periodicity in spanwise)
- No-slip isothermal walls
- Suction and blowing at the wall

DNS simulations: grid and excitation

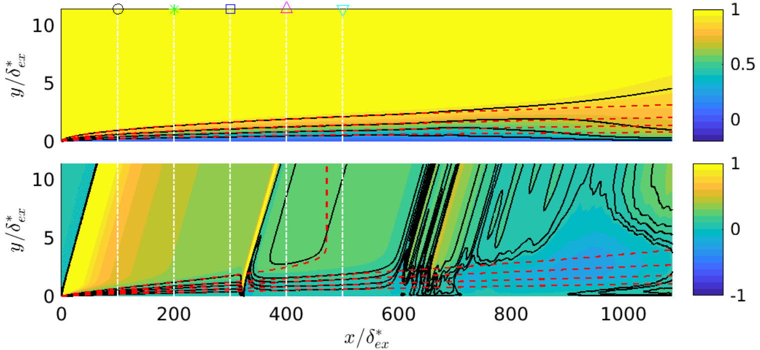
	N_x	N_y	N_z	L_x/δ	L_y/δ	L_z/δ	Δx^+	Δy_w^+	Δy_e^+	Δz^+
Air	7700	300	400	75.2	2.13	2.17	3.76	0.26	5.1	2.09
PP11	14336	320	280	90.1	1.75	1.56	8.12	0.65	18	9.77

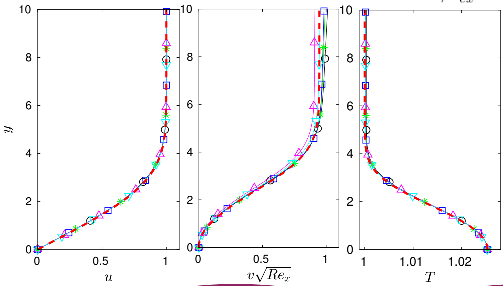


	Air	PP11
A/U_∞	0.002	0.02
a_{2D}	0	1
a_{3D}	1	0.05
a_H	0	0.05
$\beta_0 \delta^*_{\text{forc}}$	0.3	0.3
$\omega_0 \delta^*_{\text{forc}}/U_\infty$	0.15	0.6
$Re_{\delta^*_{\text{forc}}}$	3000	1200

$$v_w = A f(x) g(z) \Big\{ a_{2D} \cos(\omega_0 t) + a_{3D} \cos(\omega_0 t \pm \beta_0 z) + \sum_{m=1}^{5} a_H \cos(\omega_0 t \pm 2m\beta_0 z) \Big\}$$

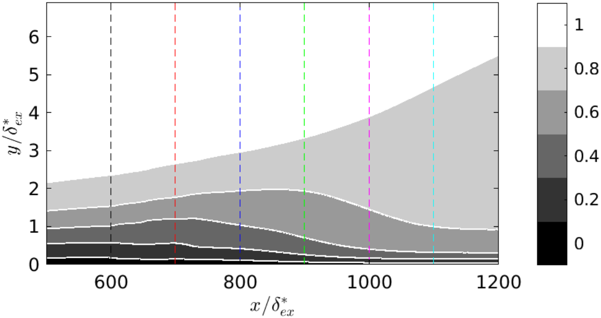
Laminar regime for dense-gas

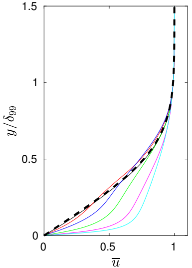


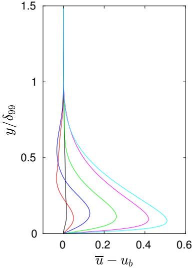


- good agreement with similarity solution up to $x/\delta^*_{ex} \approx 550$, *despite leading edge shock (viscous interaction) and excitation shock*
- strong mean-flow distorsion for $x/\delta^*_{ex} > 550$

Mean flow distortion (MFD)







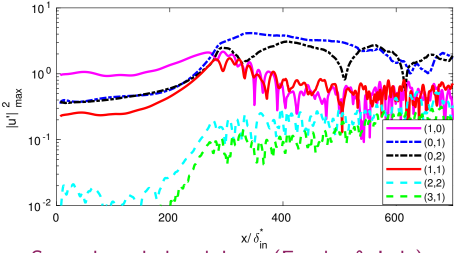
- after MFD, the base flow is completely different and the 2D unstable mode (supersonic or second mode†) is no more sustained and rapidly falls down
- streaky structures are generated due to the presence of 3D perturbations (oblique waves)

† Sivasubramanian & Fasel, "DNS of transition in a sharp cone boundary layer at Mach 6: fundamental breakdown", J. Fluid Mech., 768:175–218, 2015

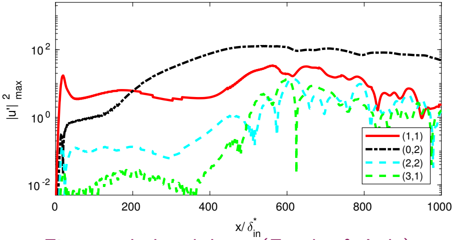
Modal analysis: $(n, k) = (\omega/\omega_0, \beta/\beta_0)$

Streamwise development of the maximum u-velocity disturbance amplitude

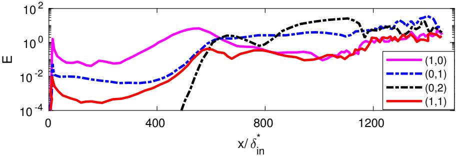
Supersonic-mode breakdown (DNS dense gas)



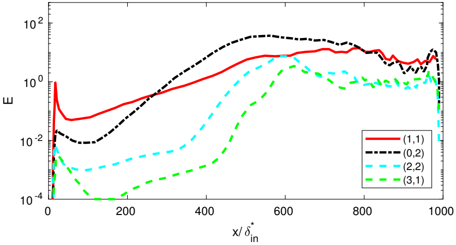
First-mode breakdown (DNS perfect gas)



Second-mode breakdown (Franko & Lele)



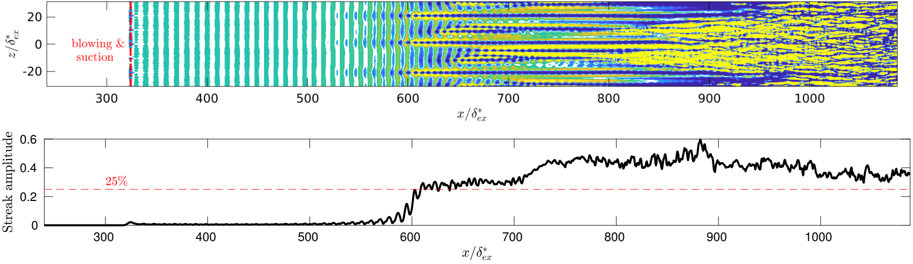
First-mode breakdown (Franko & Lele)



- 2D mode (———), oblique mode (———)
- stationary **streak** modes (– · – ·, – · – ·)

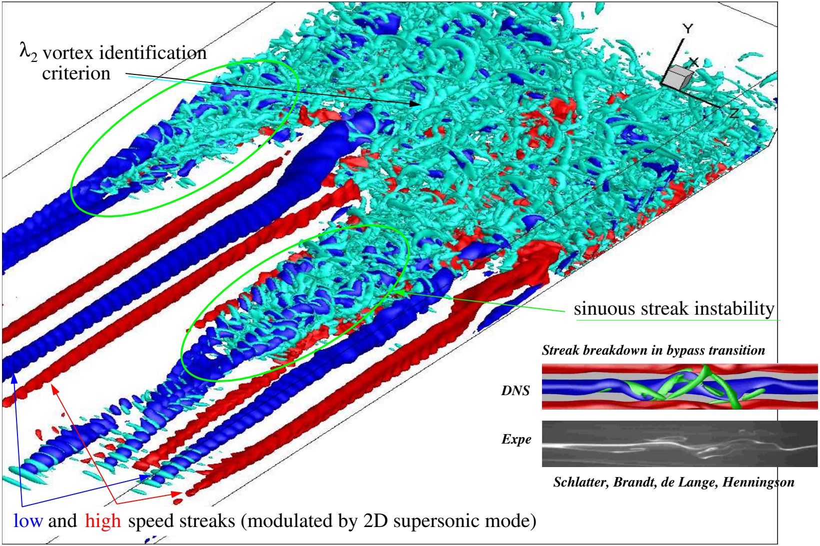
↪ similarity between supersonic-mode breakdown and second-mode breakdown

Streaks amplitude



- streak amplitude approximated as $A = \frac{1}{2U_\infty}\left[\max_{y,z}(u - u_B) - \min_{y,z}(u - u_B)\right]$
- relatively low streak amplitude
- sinuous pattern observed

Instantaneous 3D visualization

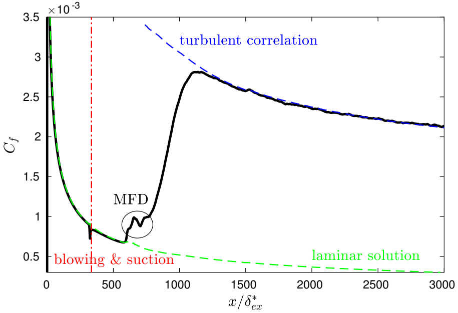


- Streak instability or transient growth? Secondary spanwise perturbation?

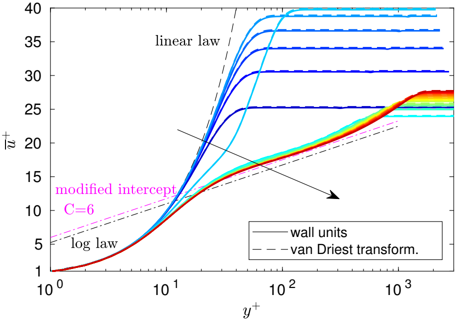
→ lift-up mechanism yields a rapid turbulent breakdown

Turbulent regime

Friction coefficient



Mean streamwise velocity



- Turbulent state is reached without overshoot (irregular breakdown pattern similar to bypass transition)
- van Driest-transformed profiles ≈ incompressible wall units scaling (despite M=6)
- more details for turbulent state in Sciacovelli, Gloerfelt, Passiatore, Cinnella & Grasso, "Numerical investigation of high-speed turbulent boundary layers of dense gases", Flow Turb. Combust., 105:555-579, 2020

- first simulation of turbulent breakdown with a supersonic mode (either for dense gas or perfect gas)
- bear similarities with second-mode breakdown, which confirms that it belongs to "acoustic modes"
- in particular: no direct transition but strong mean flow distorsion $\longrightarrow$ streaks of low amplitude $\longrightarrow$ breakdown through lift-up mechanism
- acoustic radiation from the instability wave; no overshoot in the friction evolution
- transition with acoustic mode is not very efficient $\longrightarrow$ more probably freestream transition
- new project REGAL-ORC: comparison of freestream-transition simulations with experiments in CLOWT facility (FW-Muenster)