Over-expanded nozzle dynamics

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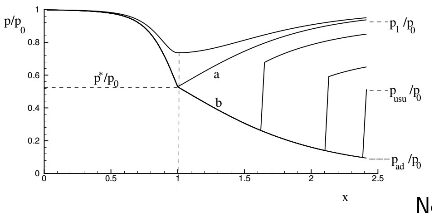
Abstract

During start-up and shut-down transients shock occurs inside the divergent duct, interacting with boundary layer. Many studies, devoted for 60 years to the dynamics of these interactions, lead to blame a low-frequency unsteadiness, associated to a self-sustained azimuthal mode, for the generation of **side loads***, that represent restrictive design constraints. As part of the Aérodynamique des Tuyéres et Arriéres-Corps (ATAC) program driven by CNES, the intent of this thesis work is to perform fully-3D linear stability analysis to investigate the potentially globally unstable nature of this mode.*

Physical Background:



Performance at different NPR (p_0/p)

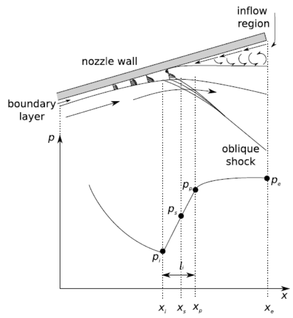
- adapted (supersonic) flow: $NPR = p_0/p_{ad}$
- oblique shock at exit: $NPR = p_0/p_{usu}$
- pure subsonic flow: $NPR \leq p_0/p_l$
- super/**subsonic** flow with outer/**inner** shock: $p_0/p_l < NPR < p_0/p_{usu}$

$\Downarrow$

Non-axis-symmetric internal pressure distribution$\rightarrow$ **side loads**

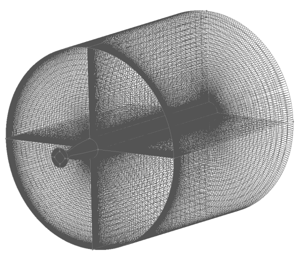
Shock wave-Boundary layer interaction (SWBLI)

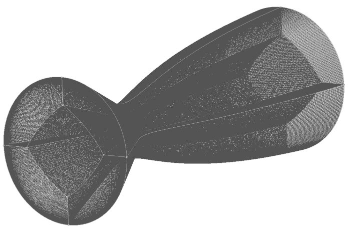
- **Free Shock Separation (FSS)**: flow accelerates against an adverse pressure gradient due to the supersonic expansion and causes the boundary-layer thickening. Compression waves originating from the deflected mean flow then coalesce into an oblique shock. Separation occurs with no reattachment.



Side loads as effect of **SWBLI**

Nonlinear Unsteady Dynamics: Hybrid RANS/LES Calculations





- CNES geometry
- NPR $= 9 < p_0/p_{ad}$
- Grids: $20 - 35 - 70 \times 10^6$ cells
- DDES

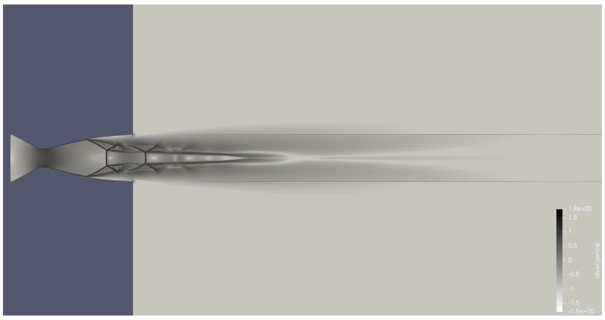


Figure: Unsteady mean-flow solution. Pseudo-Schlieren visualisation

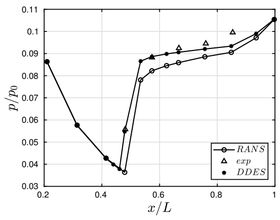


Figure: Mean pressure trends at wall

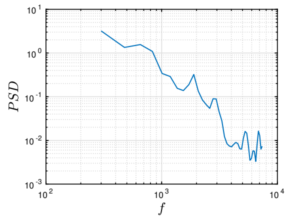


Figure: PSD for separation point computed at wall

Phoenix - Code Features

- Compressible, 3D finite-volume Navier-Stokes solver for multiblock, structured grids
- Spatial discretisation: Jameson (3rd order), Roe + MUSCL reconstruction (up to 3rd order) to calculate convective and diffusive fluxes
- Temporal discretisation: global time stepping (GTS), dual time stepping (DTS)
- Turbulence models: SA, SA + Edwards, DES, DDES
- Parallelised (MPI libraries)
- Linearised Navier-Stokes solver (spatial scheme, boundary conditions and turbulence models)
- Eigenvalue problem solver: Encapsulated Arnoldi algorithm

Linear Stability Analysis: methodology

1) Computation of the equilibrium solution of Navier-Stokes equations, called baseflow:

$$\underbrace{\frac{\partial \mathbf{q}}{\partial t} = \mathcal{R}(\mathbf{q}) \qquad \mathbf{q} = [\rho, \rho\mathbf{u}, \rho E, \rho\nu]^T}_{\text{Nonlinear solver}} \Longrightarrow \mathbf{q_b}(\mathbf{x})$$

2) Computation of perturbation about the baseflow:

$$\underbrace{\frac{\partial \mathbf{q}'}{\partial t} = \mathcal{J}(\mathbf{q}') \qquad \mathcal{J} = \partial\mathcal{R}/\partial\mathbf{q}|_{\mathbf{q_b}}}_{\text{Linearised solver}}$$

- If we separate the spatial behaviour from the temporal one:

$$\mathbf{q}'(\mathbf{x}, t) = \hat{\mathbf{q}}(\mathbf{x})e^{\lambda t}$$

3) Computation of spatial distribution ($\hat{\mathbf{q}}$), growth rate (σ) and frequency (ω) of the perturbation:

$$\underbrace{\mathcal{J}(\hat{\mathbf{q}}) = \lambda\hat{\mathbf{q}} \qquad \lambda = \sigma + \mathbf{i}\omega}_{\text{Eigenvalue problem solver}}$$

Conclusions

✓ good comparison in terms of PSD and pressure field with experiments

✓ separation point and Mach disks positioning in agree with experiments

? Topology of unsteady flow analysis is ongoing (global movement concerning the system shear layers-shocks, etc..)

Perspectives

- computation of unsteady solution with a 70 millions cells grid
- well-converged base flow computation
- linear stability analysis
- physical analysis (screech, transonic resonanc,etc..)
- same study for different values of NPR (6-12)

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