15th CEAS-ASC Workshop
1st Scientific Workshop of X-NOISE EV
Acoustic Liners and Associated Propagation Techniques
EPFL, Lausanne
October 13-14, 2011

Computational tools for modeling acoustic liners and propagation: Review of some key ingredients and challenges

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Free Field Technologies, Belgium

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Summary

- Modeling acoustic treatments
- Acoustic propagation with flow
- Flow conditions:
  - Assessing acoustic attenuation with or without shear layers
  - Incorporating or not vorticity into acoustic propagation models
- Alternative frequency-domain and time-domain approaches:
  - Convected wave equation model (Actran TM)
  - LEE model (Actran DGM)
- Modeling radiation boundary conditions:
  - Infinite elements
  - Buffer zones
- Modal duct excitations
- Software requirements:
  - Parallelism and HPC solvers
  - Energy indicators
- Next challenges

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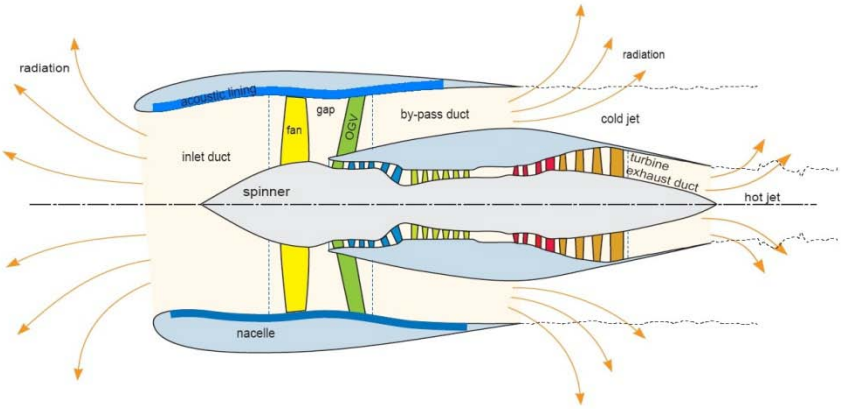
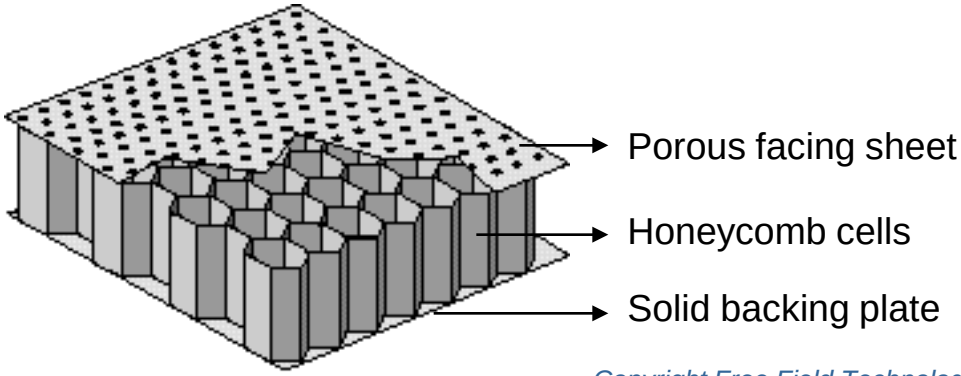
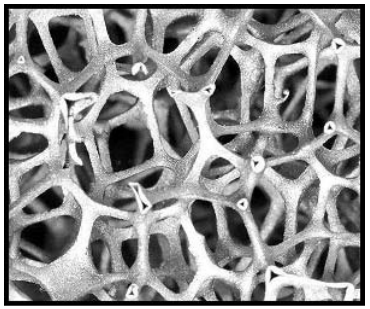
Context

- Various aircraft noise sources
- Fan noise = dominant component at take-off/landing for HBPR turbofan engines
- Attenuation using liners (engine intake, exhaust ducts)
- Typical (locally reacting) acoustic liners:
  - SDOF
  - DDOF or MDOF
- Need for efficient models incorporating liners:
  - Extended frequency range
  - Non-uniform treatments
  - Adaptive liners
  - New absorbing materials (bulk reacting)
  - Optimization







Metal foam

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Noise reduction technologies

- Liners and noise reduction technologies:

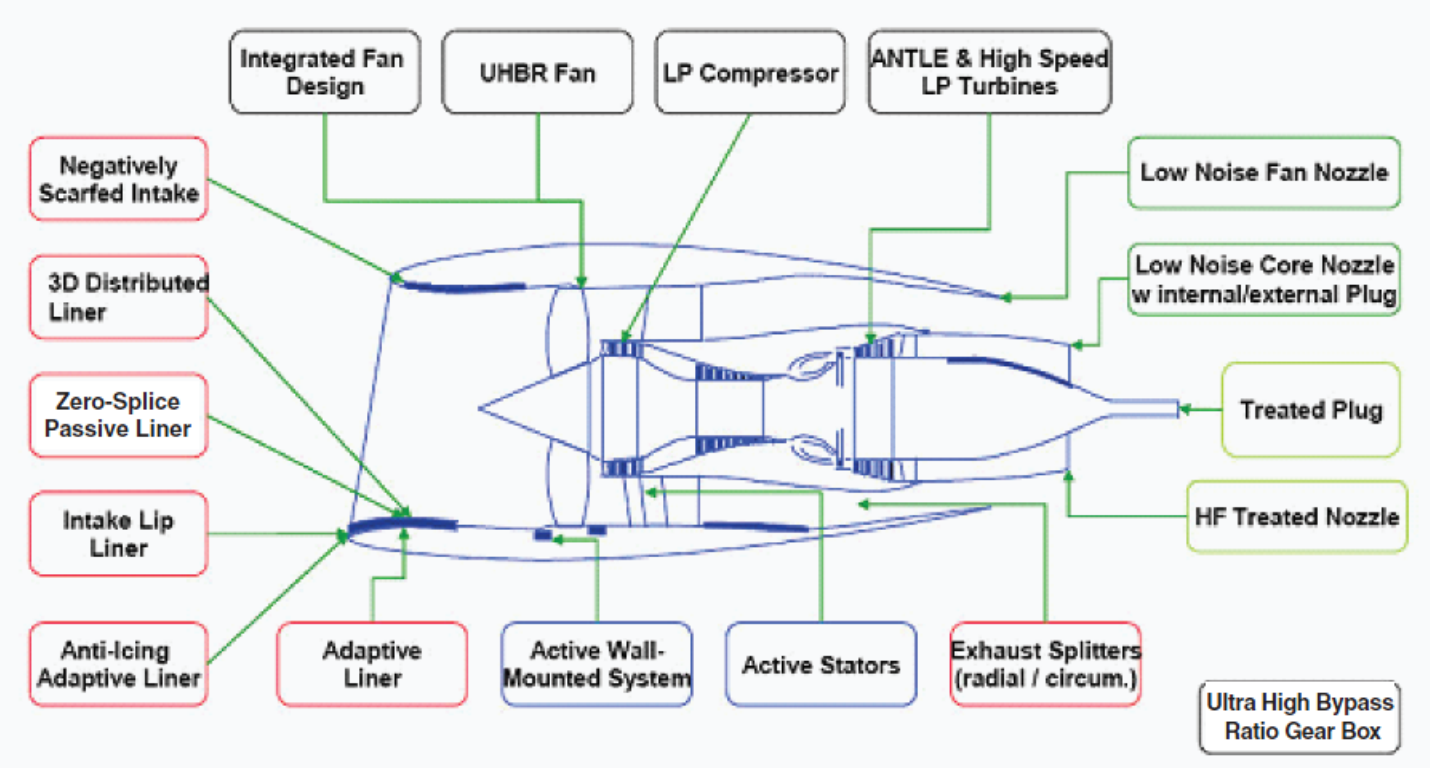

FIGURE 5-9 Engine/nacelle noise reduction technologies. UHBR = ultra high bypass ratio. Source: SBAC (2009).

(from « Technology for a Quieter America », National Academy of Engineering, 2010)

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Modeling liners

- Locally reacting liners:
  - Frequency domain:
    - No flow case: $$p(\omega) = z(\omega) v_n(\omega)$$
    - Flow case (Myers): $$v_n(\omega) = \frac{p(\omega)}{z(\omega)} + v_0 \cdot \nabla\left(\frac{p(\omega)}{i\omega z(\omega)}\right) - \frac{p(\omega)}{i\omega z(\omega)} n \cdot (n \cdot \nabla v_0)$$
  - Time domain:
    - Convolution integral: $$p(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} z(t-\tau) v_n(\tau) d\tau$$
  - Comments:
    - Emergence of refined (DNS) models for predicting impedance (Zhang-Codony)
    - Stability issues of Myers boundary condition (*)
    - Need for stable/causal z(t) models (Tam-Auriault, Ozyoruk-Long, Richter, etc)
- Non-locally reacting (or bulk reacting) liners:
  - More advanced models (Biot for porous materials)

(*) see Brambley (AIAA paper 2010-3942) for improved Myers bc

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Modeling acoustic propagation with flow

- LEE model (unknowns = p', v' and ρ') ← Actran DGM

$$\frac{\partial \rho'}{\partial t} + \nabla \cdot (\rho' v_0 + \rho_0 v') = 0$$

$$\rho_0 \left(\frac{\partial}{\partial t} + v_0 \cdot \nabla \right) v' + \rho_0 (v' \cdot \nabla) v_0 + \rho' (v_0 \cdot \nabla) v_0 + \nabla p' = 0$$

$$\left(\frac{\partial}{\partial t} + v_0 \cdot \nabla \right) p' + v' \cdot \nabla p_0 + \gamma p_0 (\nabla \cdot v') + \gamma p' (\nabla \cdot v_0) = 0$$

- Convected Wave Equation model (unknown = ϕ') ← Actran TM

$$p' = c_0^2 \rho' = -\rho_0 \left(\frac{\partial}{\partial t} + v_0 \cdot \nabla \right) \phi'$$

$$\frac{D}{Dt} \left(\frac{\rho_0}{c_0^2} \frac{D\phi'}{Dt} \right) - \nabla \cdot (\rho_0 \nabla \phi') = 0$$

Further assumptions:

- Homentropic case
- Irrotational flow

- Main issues:
  - Model sizes (LEE – 4 or 5 dofs/node, CWE – 1 dof/node)
  - Effect of boundary layers on acoustic propagation/attenuation?

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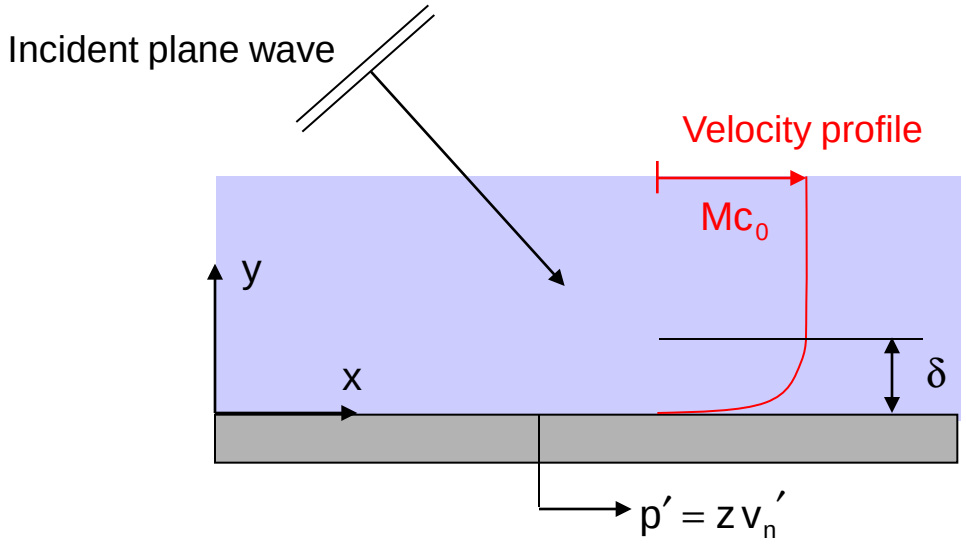
Evaluation of propagation models

- Context: evaluation of the reflection coefficient along a treated surface
- Objective: assessment of boundary layer thickness (δ) and flow velocity (M)
- Models:
  - Pridmore-Brown model (1958) → reference
  - Myers model (1980) → valid for an infinitely thin boundary layer
  - Möhring model (1999) and extended Möhring models → valid for a rotational flow
  - Convected wave equation (velocity potential) → valid for an irrotational flow



$$v_0 = \begin{pmatrix} U(y) \\ 0 \\ 0 \end{pmatrix}$$

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Pridmore-Brown model

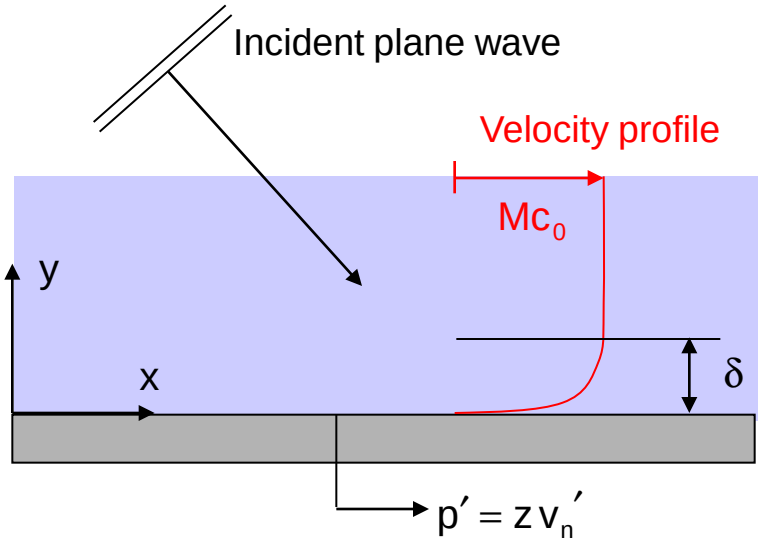
- Assumption of a sheared flow along x only + propagating wave along x:

$$v_0^T = \begin{pmatrix} U(y) & 0 & 0 \end{pmatrix} \qquad p'(x,y,\omega) = p'(y)\, e^{-ik_x x} e^{+i\omega t}$$

- Reference (exact!) model for this kind of flow:

$$\frac{d^2p'}{dy^2} + \frac{2k_x}{k - Mk_x}\frac{dM}{dy}\frac{dp'}{dy} + k^2\left(1 - \frac{k_x^2}{k^2}\left(1 - M^2\right) - 2M\frac{k_x}{k}\right)p' = 0$$

- Notations:
  - Mach number M
  - Wavenumber k
  - Spatial wavenumber k_x
  - Pressure p'



$$v_0 = \begin{pmatrix} U(y) \\ 0 \\ 0 \end{pmatrix}$$

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Möhring model

- (Improved) Möhring model (in terms of total enthalpy B'):

$$\frac{\partial}{\partial t}\left(\frac{\rho_0}{\rho_T c^2}\frac{DB'}{Dt}\right)+\nabla\cdot\left(\frac{\rho_0 v_0}{\rho_T c^2}\frac{DB'}{Dt}+\frac{\rho_0}{\rho_T{}^2}\Phi\nabla B'\right)=0 \quad\longrightarrow\quad \begin{aligned} p' &= f(B') \\ v' &= g(B') \end{aligned}$$

- Notations:
  - « Rotational » material derivative:

$$\frac{DB'}{Dt}=\frac{\partial B'}{\partial t}+\left(v_0+\chi_0\right)\cdot\nabla B'$$

  - « Rotational » velocity associated with acoustic phenomena:

$$\chi_0=\Omega_0^T\cdot\left(\omega_0\times v_0\right)$$

$$\Phi=\Theta_0\Omega_0-I \qquad \Omega_0=\left(\Theta_0-i\omega I\right)^{-1} \qquad \Theta_0=\begin{bmatrix}0 & +\omega_z & -\omega_y\\ -\omega_z & 0 & +\omega_x\\ +\omega_y & -\omega_x & 0\end{bmatrix} \qquad \omega_0=\nabla\times v_0=\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix}$$

Reference: C. Legendre and G. Lielens, internal report, FFT, 2011

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Möhring model / Numerical stability

- Stability of Möhring model:

$$\Omega_0^{-1} = \begin{bmatrix} -i\omega & +\omega_z & -\omega_y \\ -\omega_z & -i\omega & +\omega_x \\ +\omega_y & -\omega_x & -i\omega \end{bmatrix} \qquad \nabla \times v_0 = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$

- Evaluation of velocity field v' requires the inversion of this matrix so that

$$\det\left(\Omega_0^{-1}\right) \neq 0 \quad \Leftrightarrow \quad +i\omega^3 - i\omega\left(\omega_x^2 + \omega_y^2 + \omega_z^2\right) \neq 0$$

- Instability occurs when
  - $\omega = 0$ → zero frequency
  - $\omega_x^2 + \omega_y^2 + \omega_z^2 = \omega^2$ → magnitude of vorticity vector = angular frequency

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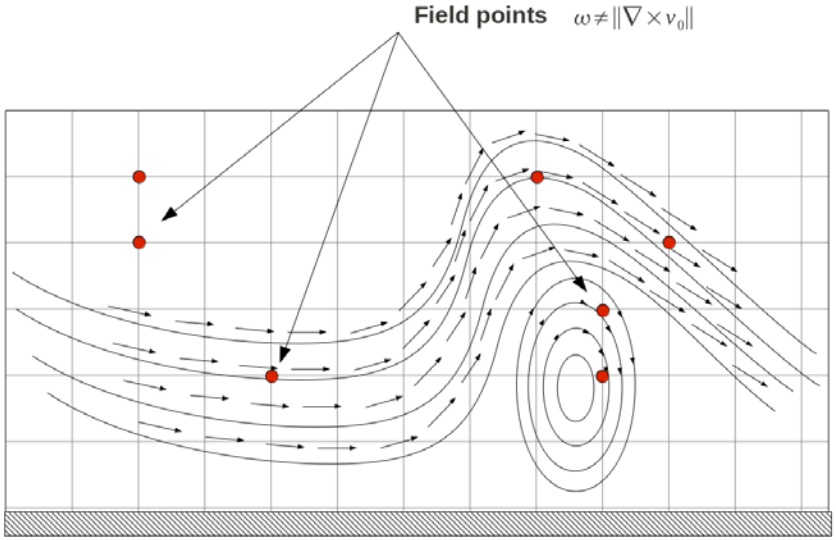
Need for a stabilization procedure

- Existence of singular points in a rotational flow:



Occurrence of points where $\omega_x^2 + \omega_y^2 + \omega_z^2 = \omega^2$

- Need for a stabilization procedure

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Regularization procedure

- Introduction of vorticity damping:

$$\Omega_0^{-1} = (1+i\varepsilon)\Theta_0 - i\omega I$$

or

$$\Omega_0^{-1} = \begin{bmatrix} -i\omega & +\omega_z(1+i\varepsilon) & -\omega_y(1+i\varepsilon) \\ -\omega_z(1+i\varepsilon) & -i\omega & +\omega_x(1+i\varepsilon) \\ +\omega_y(1+i\varepsilon) & -\omega_x(1+i\varepsilon) & -i\omega \end{bmatrix} \qquad \nabla \times v_0 = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$

- Selection of ε value:
  - Stability requirement: ε should be real
  - Accuracy requirement: low ε value (typically … 0.01 …)

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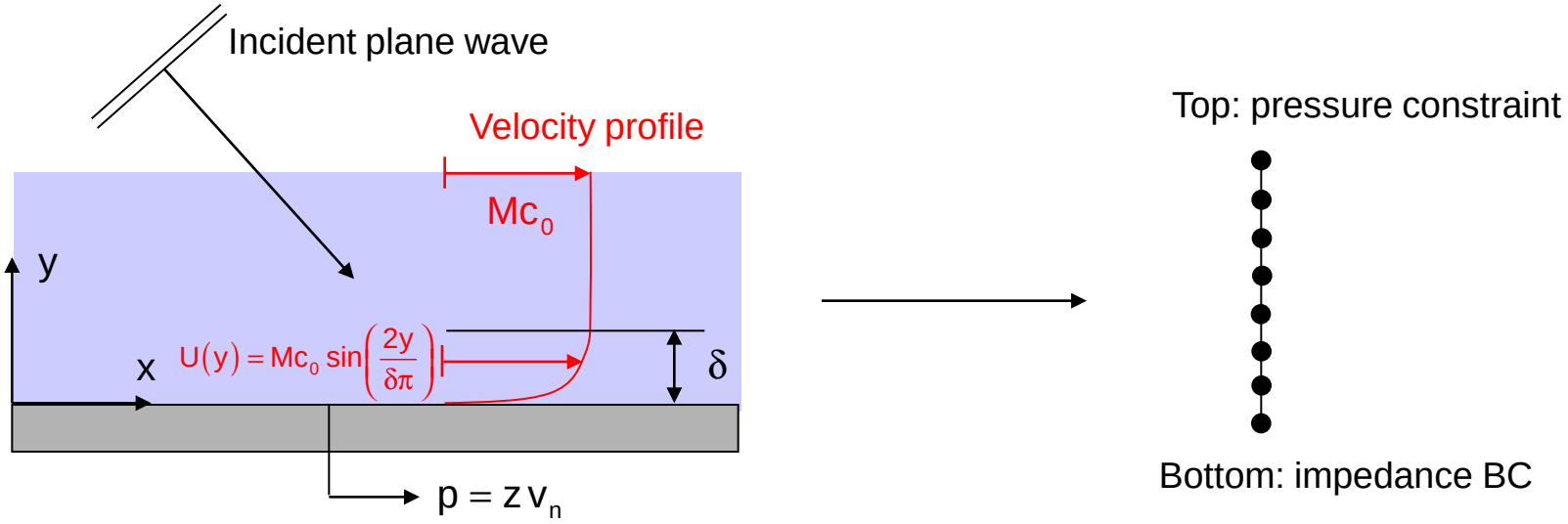
Evaluation of the reflection coefficient

- Selection of a 1-D FE model:



- Material properties:
  - Air with usual properties (c_0 = 340 m/s, ρ_0 = 1.225 kg/m^3)
  - Impedance: $z = \rho_0 c_0 (0.5+0.1i)$
- Range of input data:
  - Mach number M: 0.01 – 1 (-)
  - Vorticity damping ε : 0.1 – 1 (-)
  - Incidence angle: 0 – 90 (degrees)
  - Frequency: 1-10000 (Hz)

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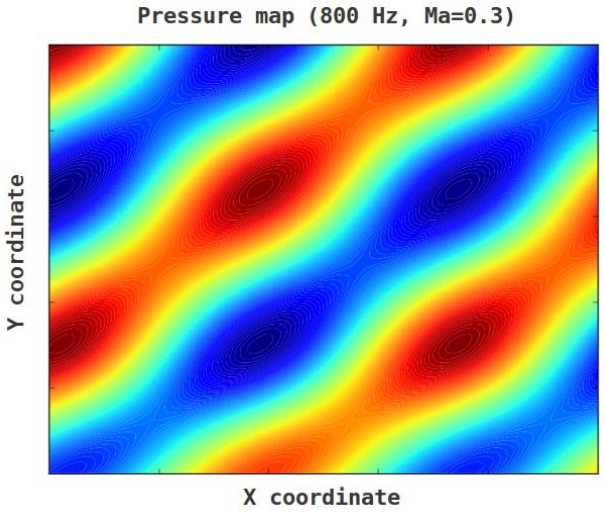
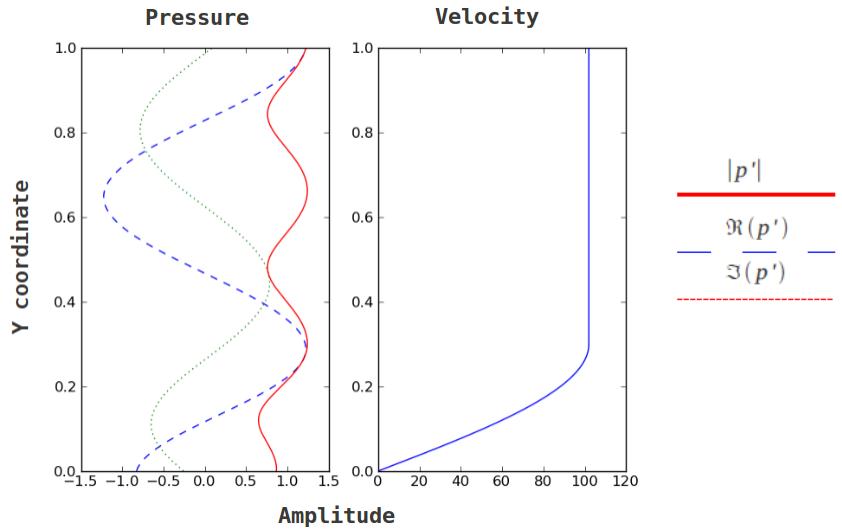
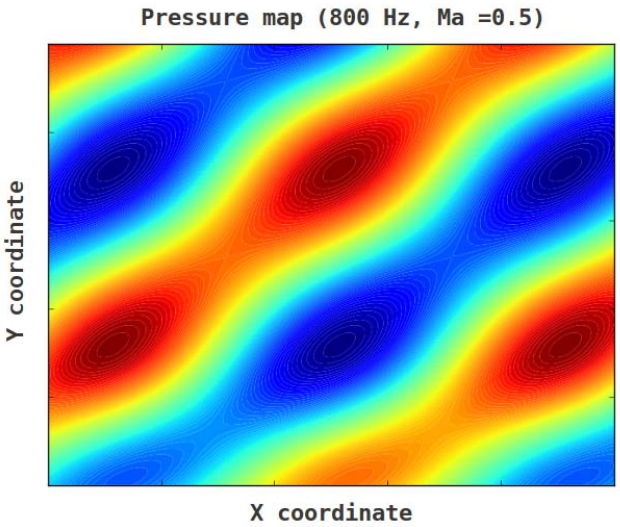
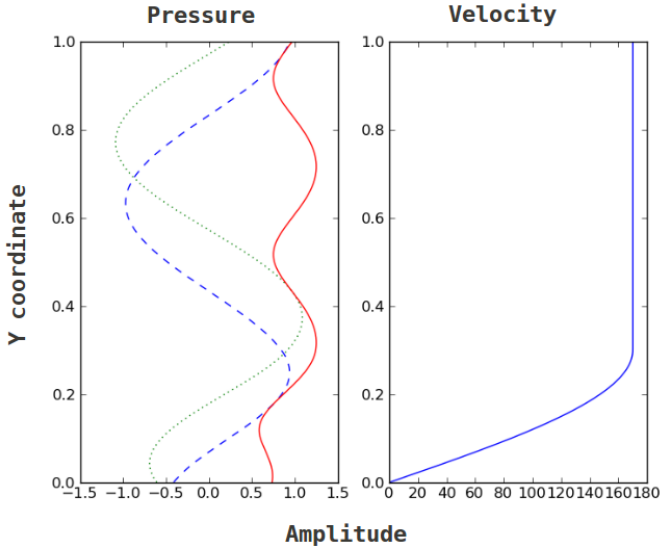
Numerical results (PMB)

- **Pridmore-Brown equation:**









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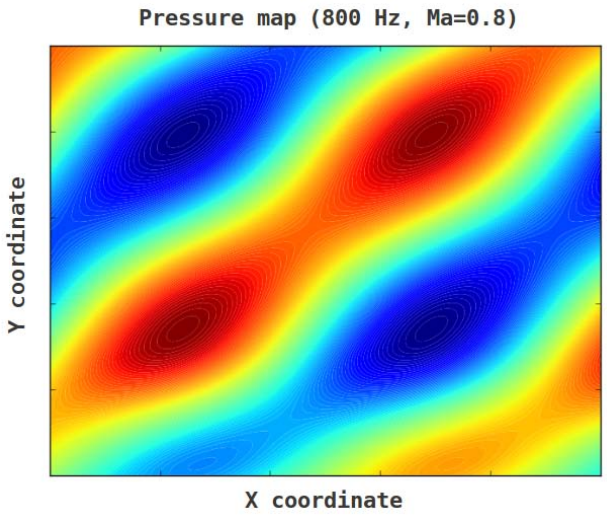
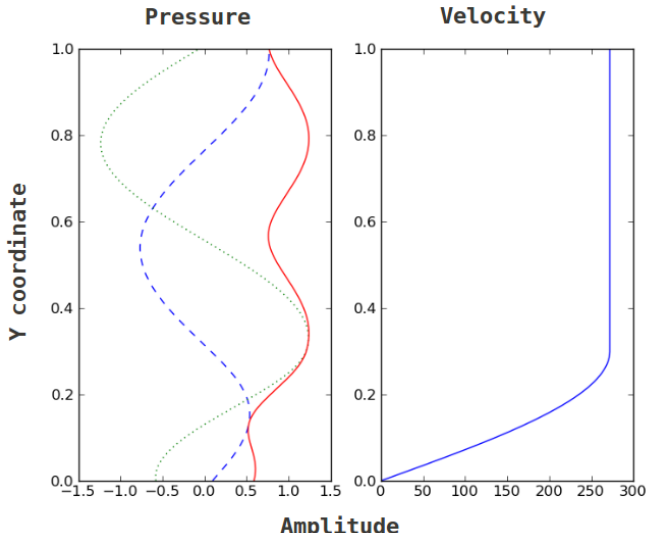
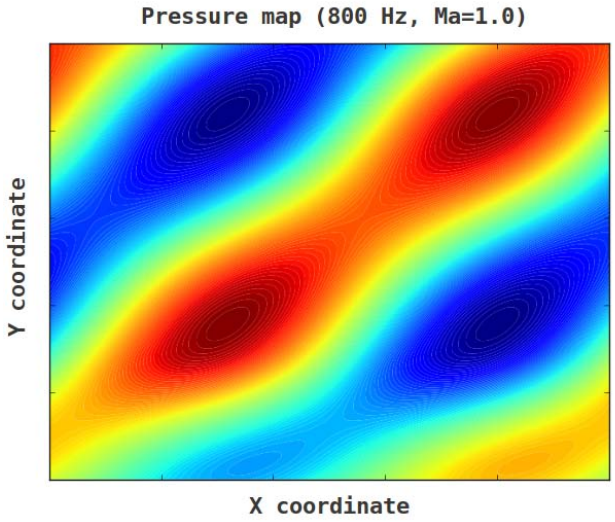
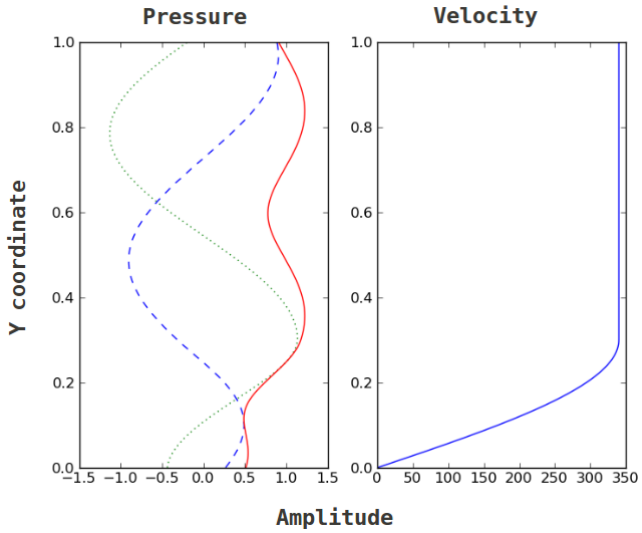
Numerical Results (PMB)

- **Pridmore-Brown equation:**









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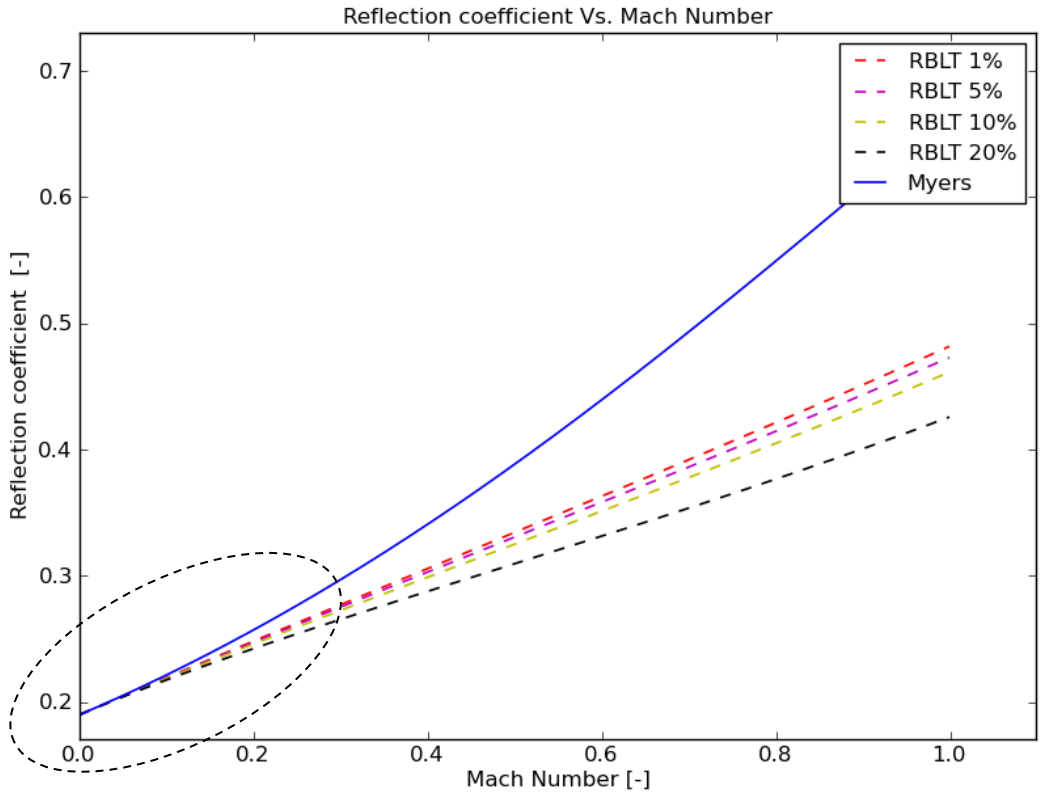
Numerical results (Myers vs. PMB)

- **Myers vs. Pridmore-Brown model:**
  - Reflection coefficient vs. Mach number



Myers ≈ Pridmore-Brown

$$RBLT = \frac{\delta}{\lambda_0} \rightarrow 0$$

Low M

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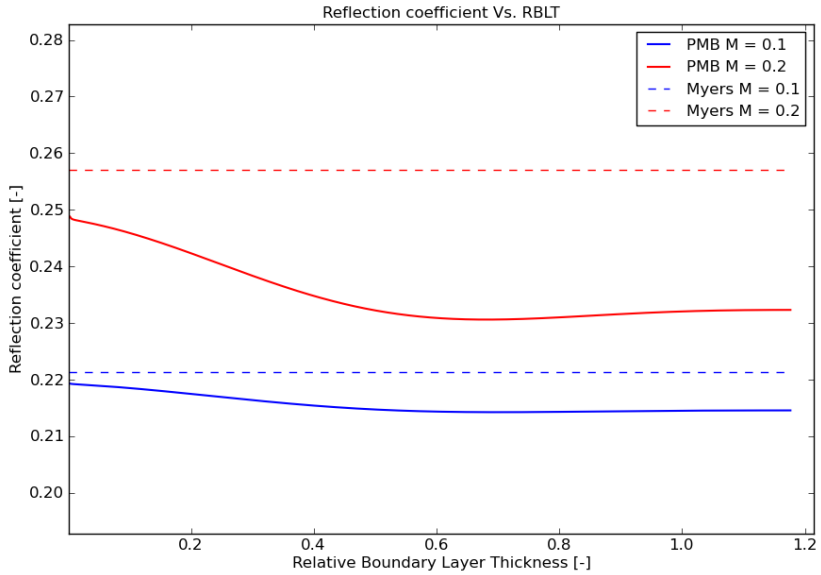
Numerical results (Myers vs. PMB)

- **Myers vs. Pridmore-Brown model:**
  - Reflection coefficient vs. relative boundary layer thickness (RBLT)

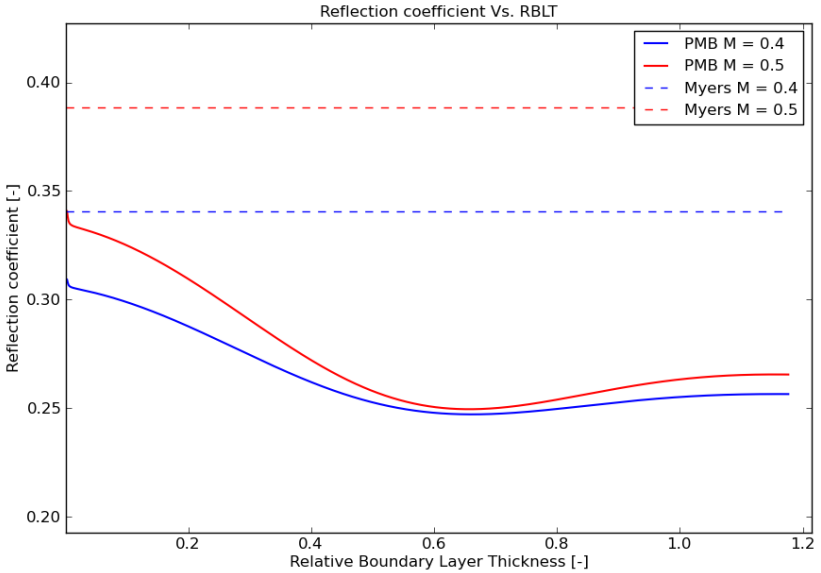
Myers $\approx$ Pridmore-Brown

$$\text{RBLT} = \frac{\delta}{\lambda_0} \rightarrow 0$$

Low M



Ma = 0.1 - 0.2



Ma = 0.4 - 0.5

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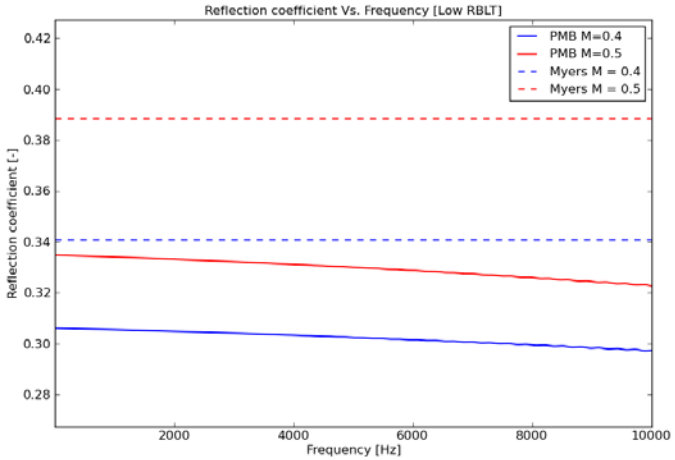
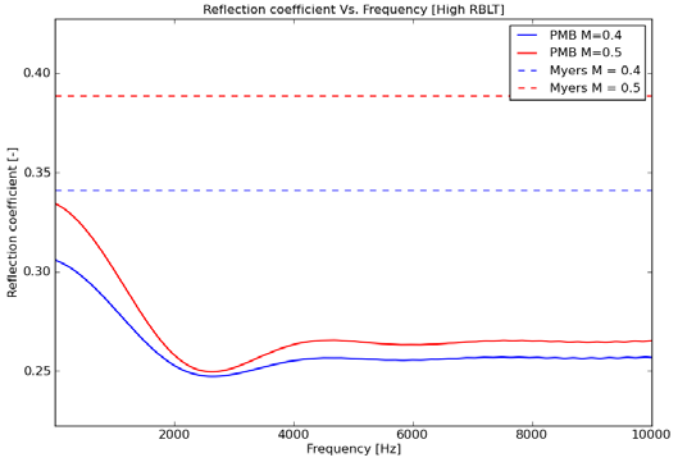
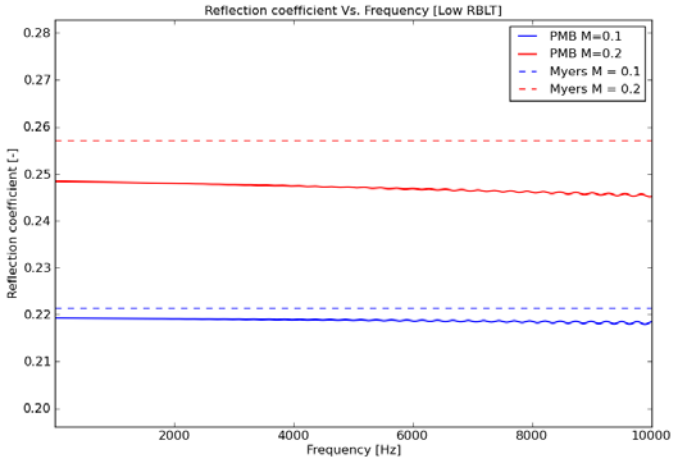
Numerical results (Myers vs. PMB)

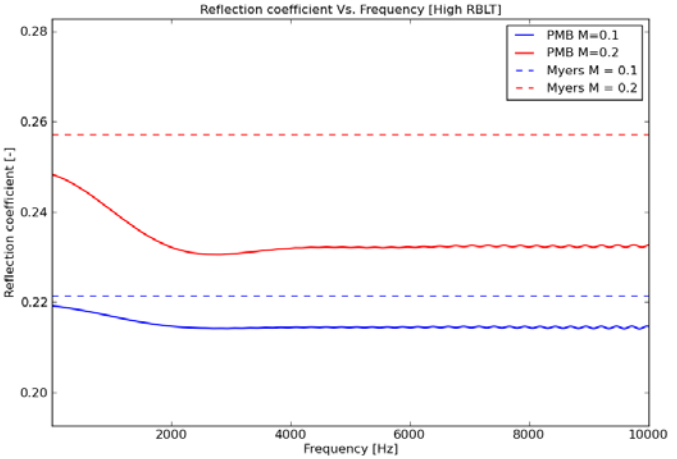
- **Myers vs. Pridmore-Brown model:**

Mach Number









RBLT

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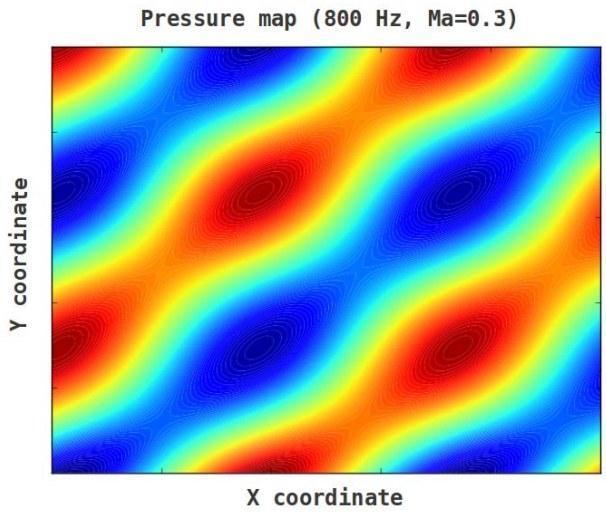
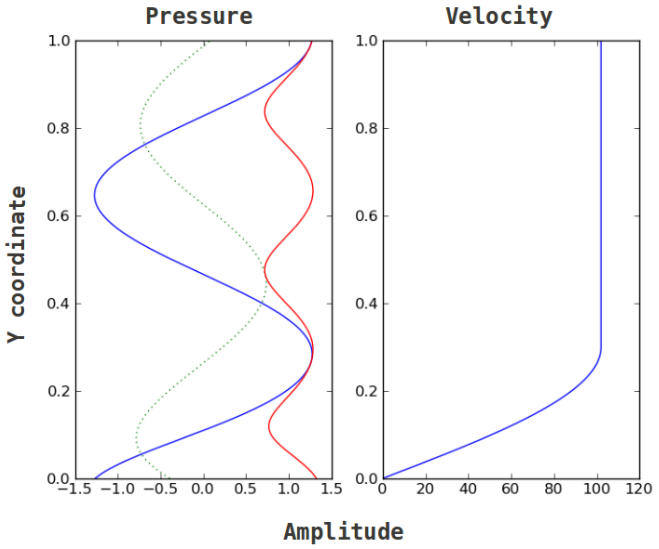
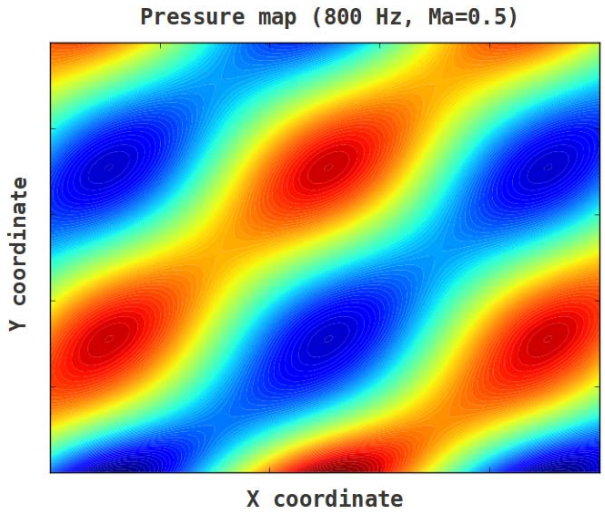
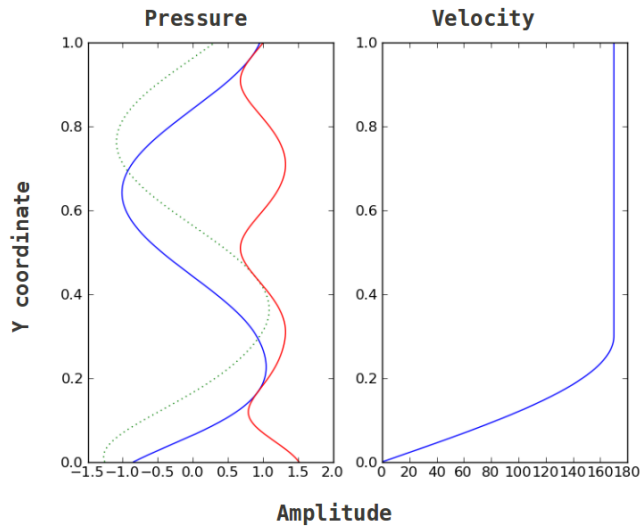
Numerical results (potential model)

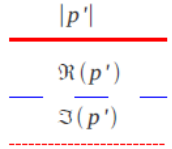
- **Potential operator** (Actran TM)**:**











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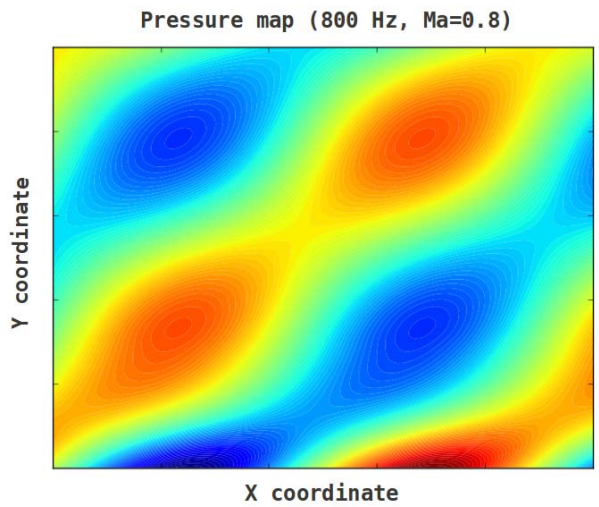
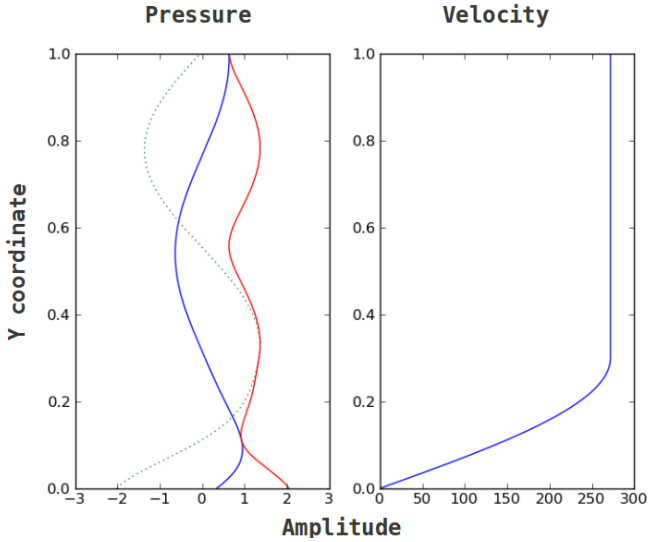
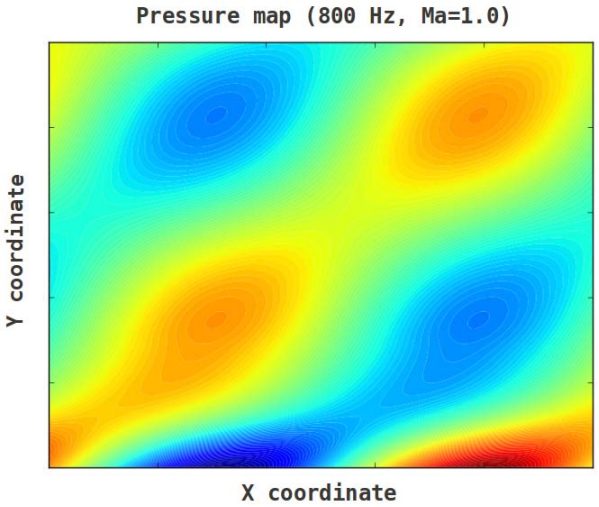
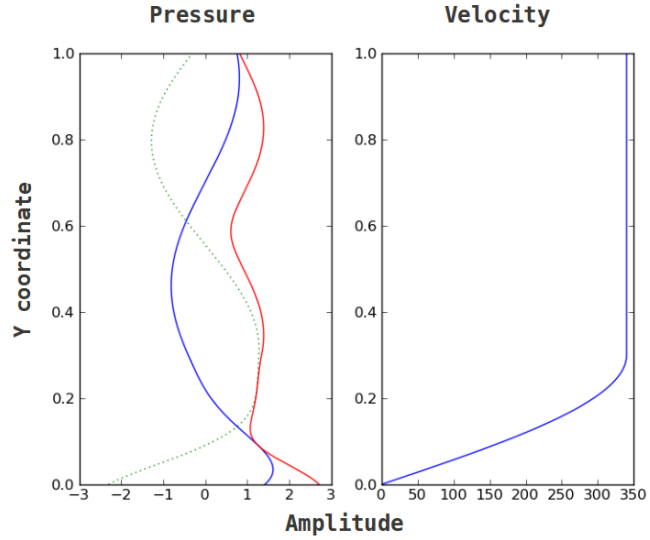
Numerical results (potential model)

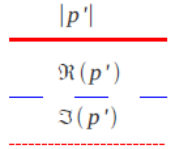
- **Potential operator** (Actran TM)**:**











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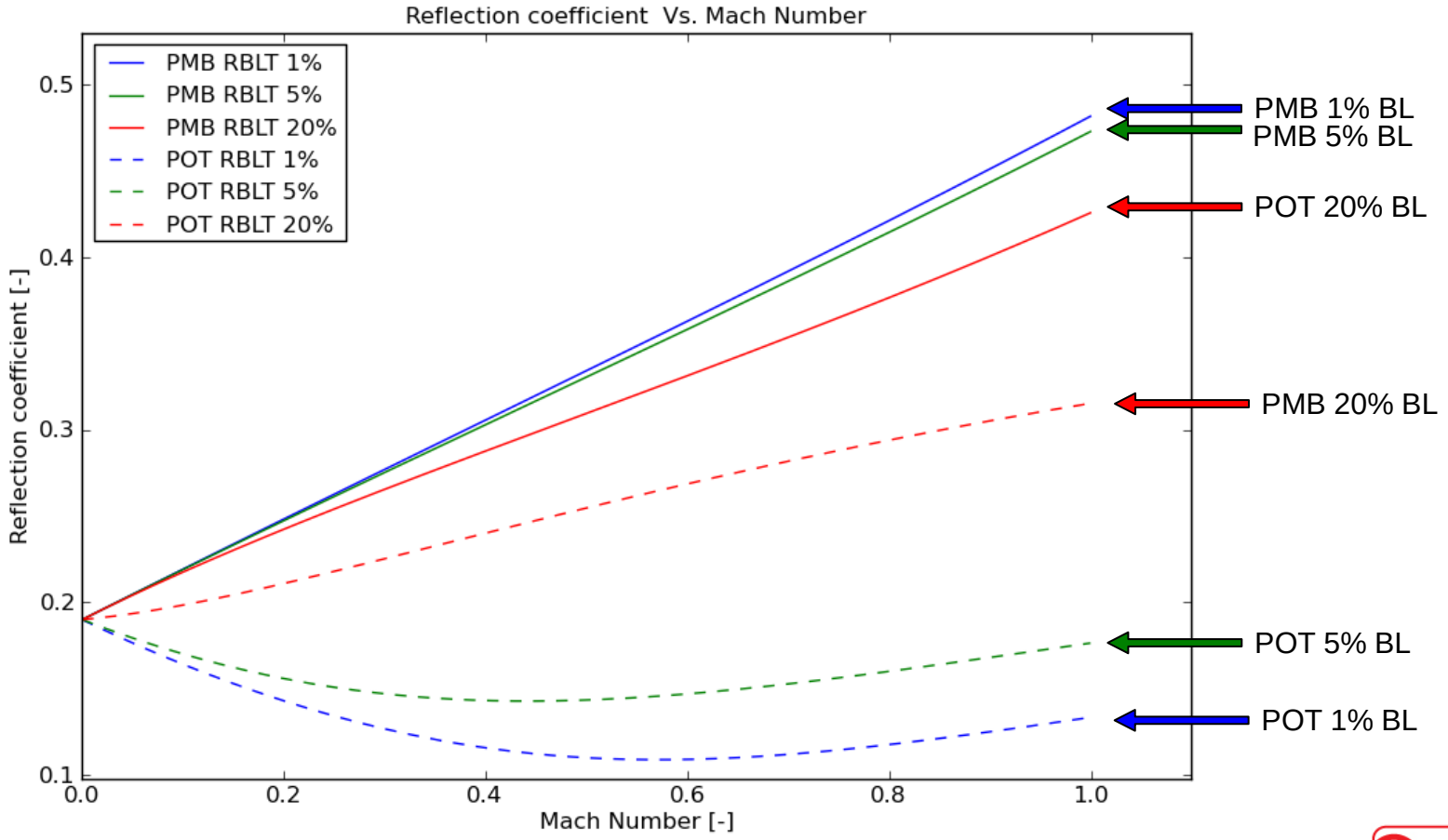
Numerical results (potential model vs. PMB)

- **Potential operator:** Reflection coefficient vs. Mach number



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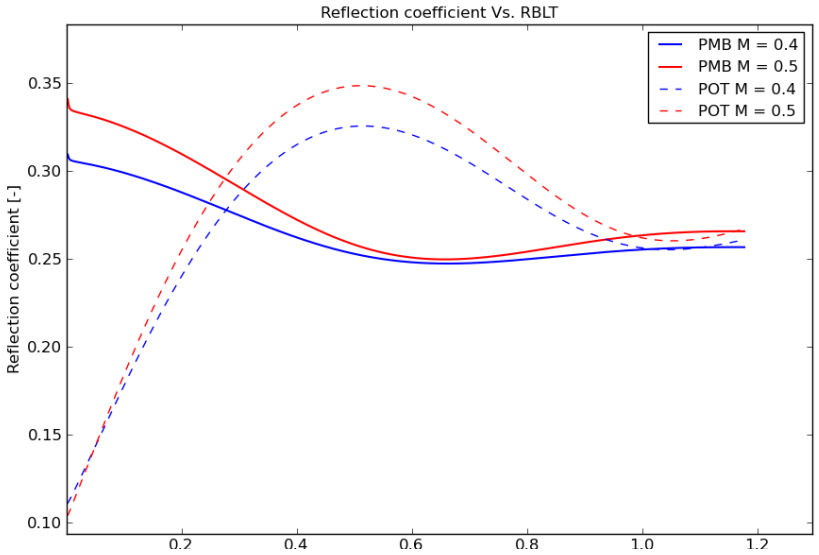
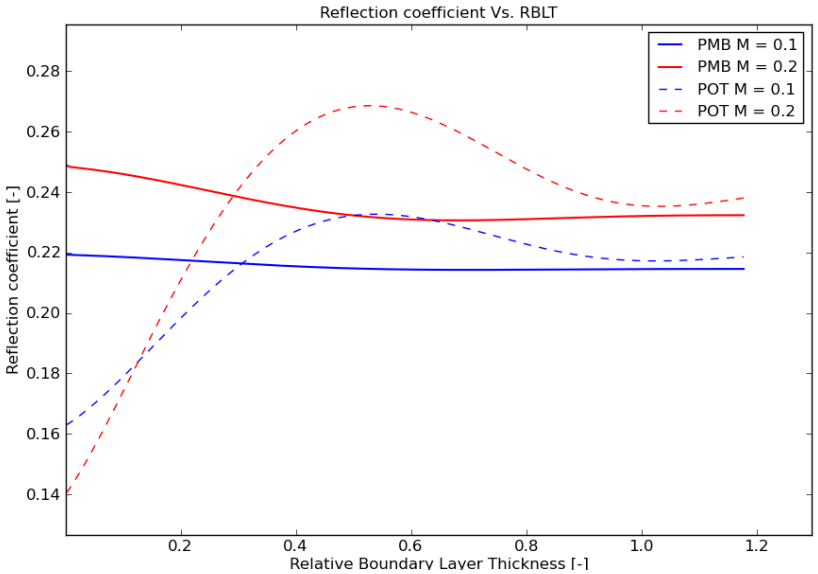
Numerical results (potential model vs. PMB)

- **Potential flow operator:** Reflection coefficient vs. RBLT

Good behaviour at high RBLT
(Low and medium vorticity)





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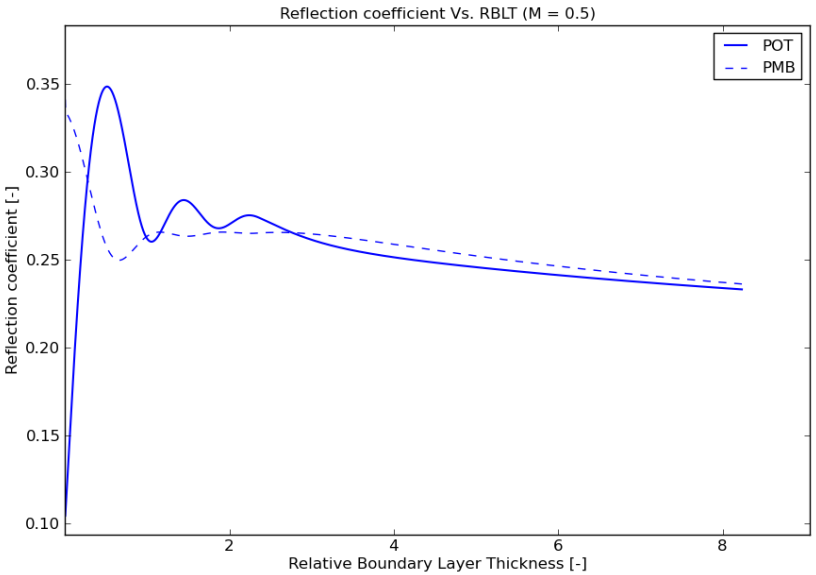
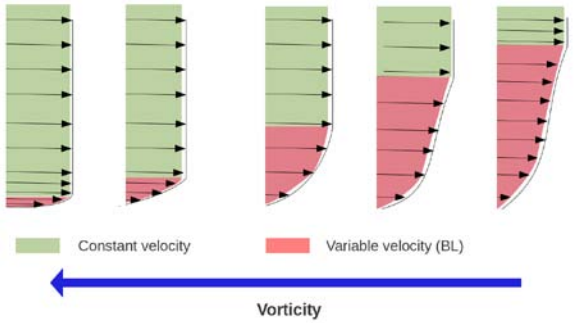
Numerical results (potential model vs. PMB)

- **Evaluation of potential operator:**
  - Reflection coefficient vs. RBLT (800 Hz):





  - If RBLT value is high (i.e. low vorticity), potential model and Pridmore-Brown model give the same results

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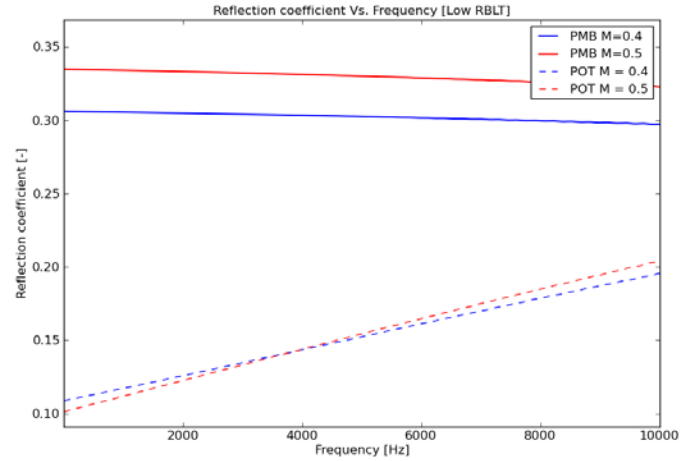
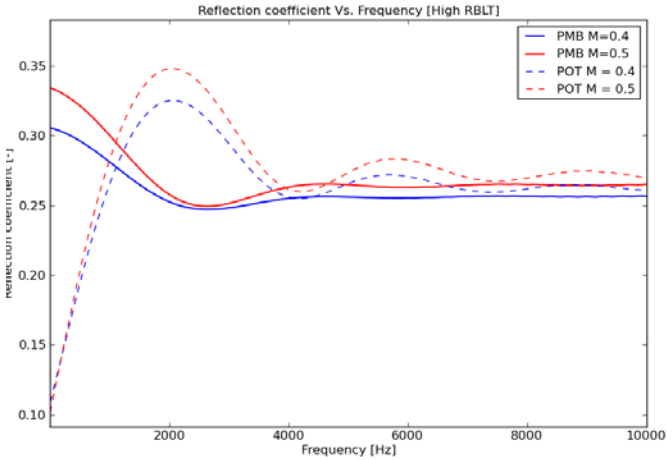
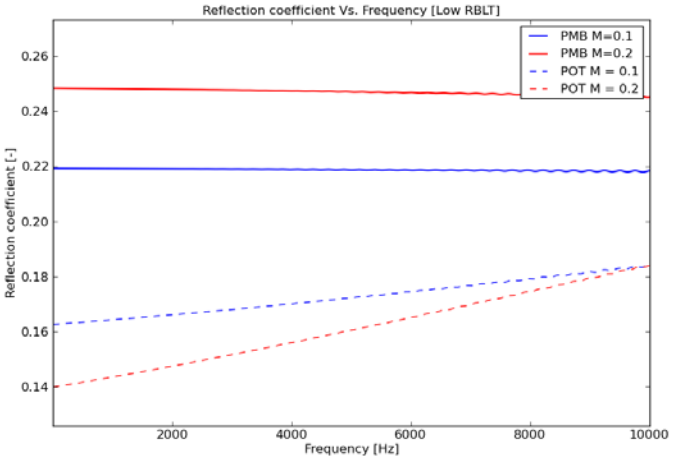
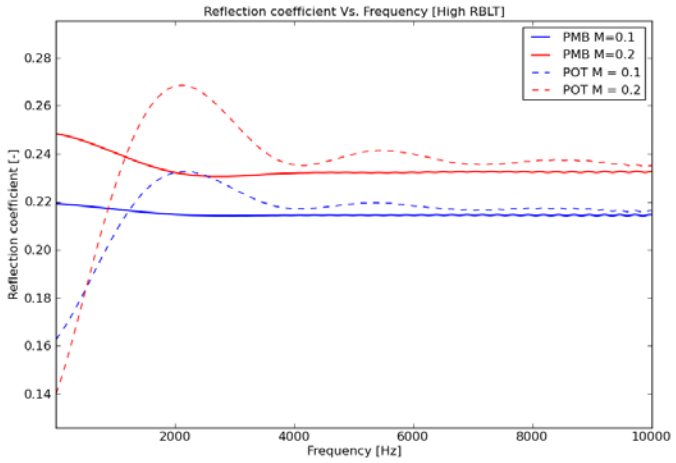
Numerical results (potential model vs. PMB)

- **Potential operator:** Reflection coefficient vs. frequency









Mach Number

RBLT

Good behaviour at high frequency

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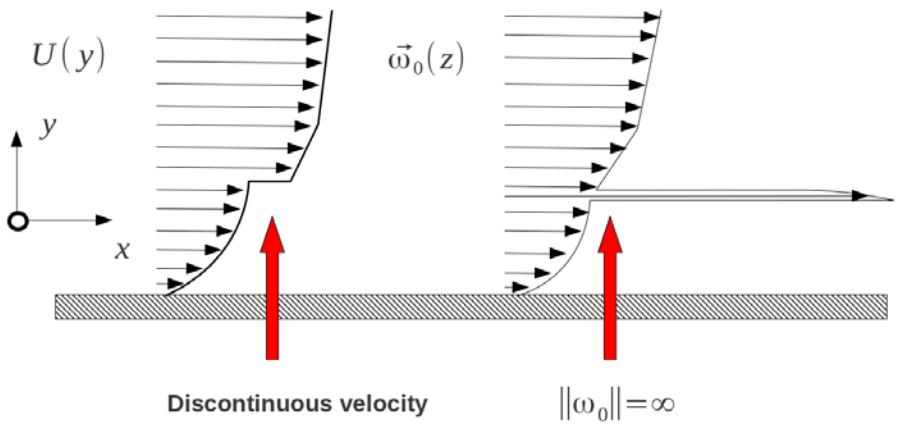
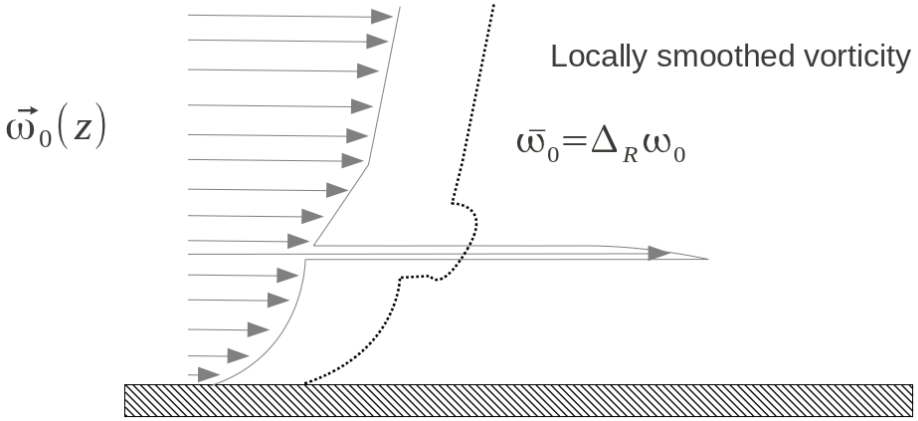
(Extended) Mohring model with regularization

- **Instability of pressure with flow vorticity**



- **Regularization procedure: smooth high vorticities …**



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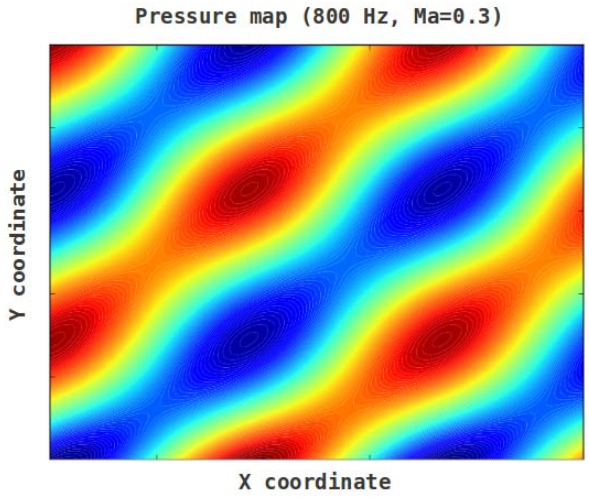
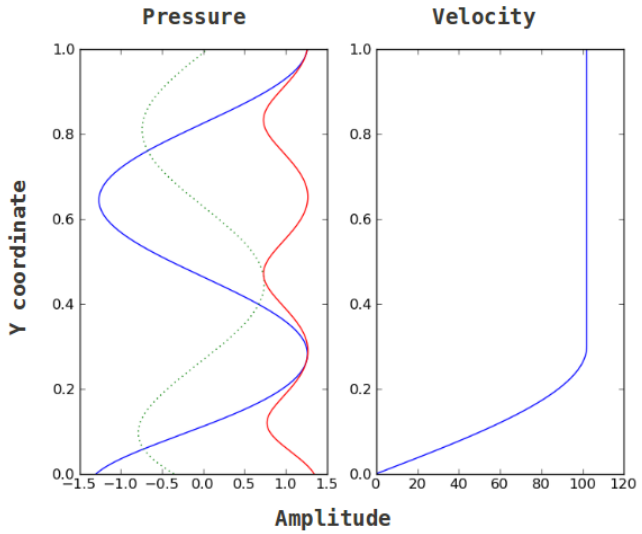
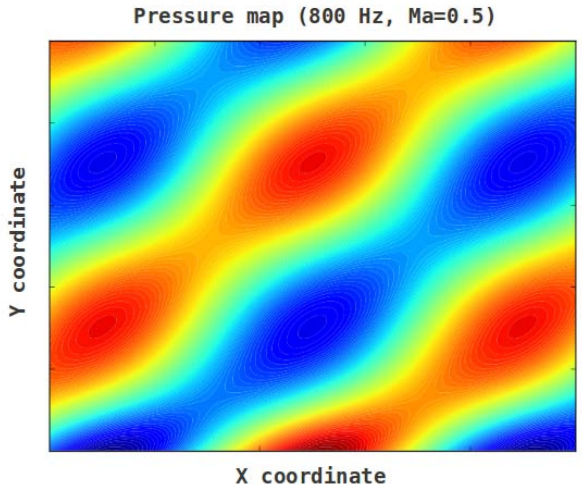
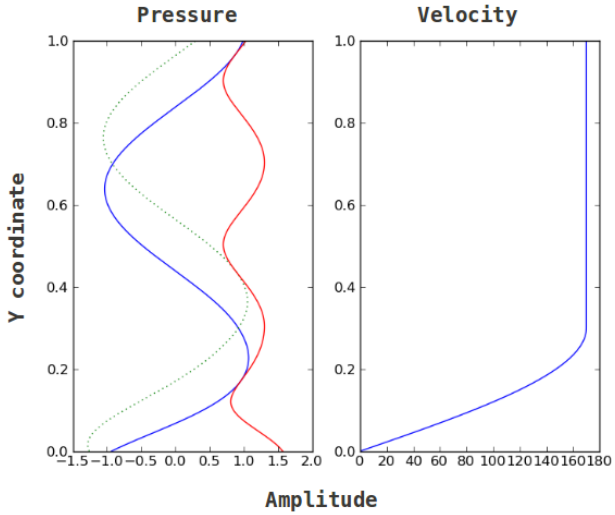
Numerical results (Möhring)

- **New Möhring equation MOH3R :**









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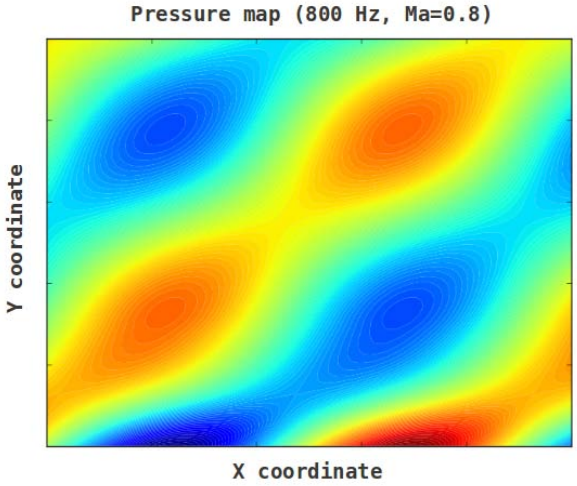
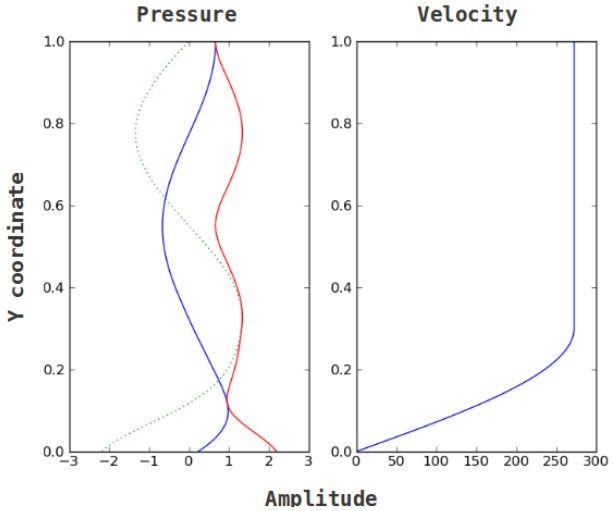
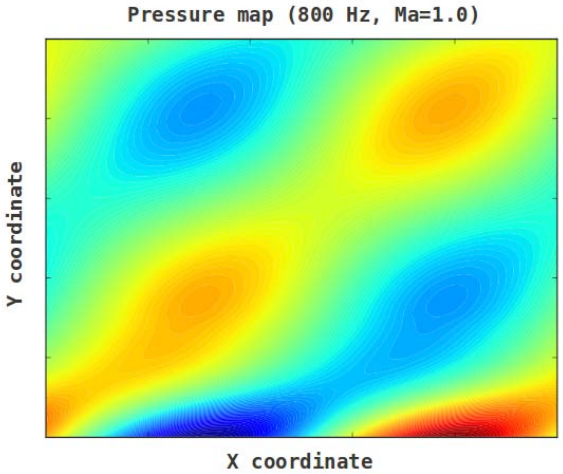
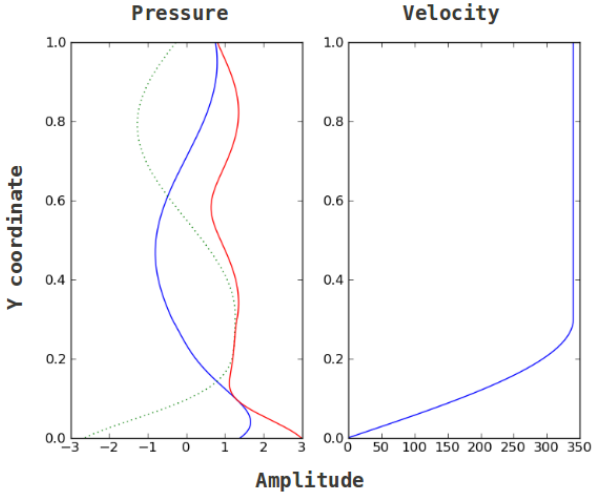
Numerical results (Möhring)

- **New Möhring equation MOH3R :**









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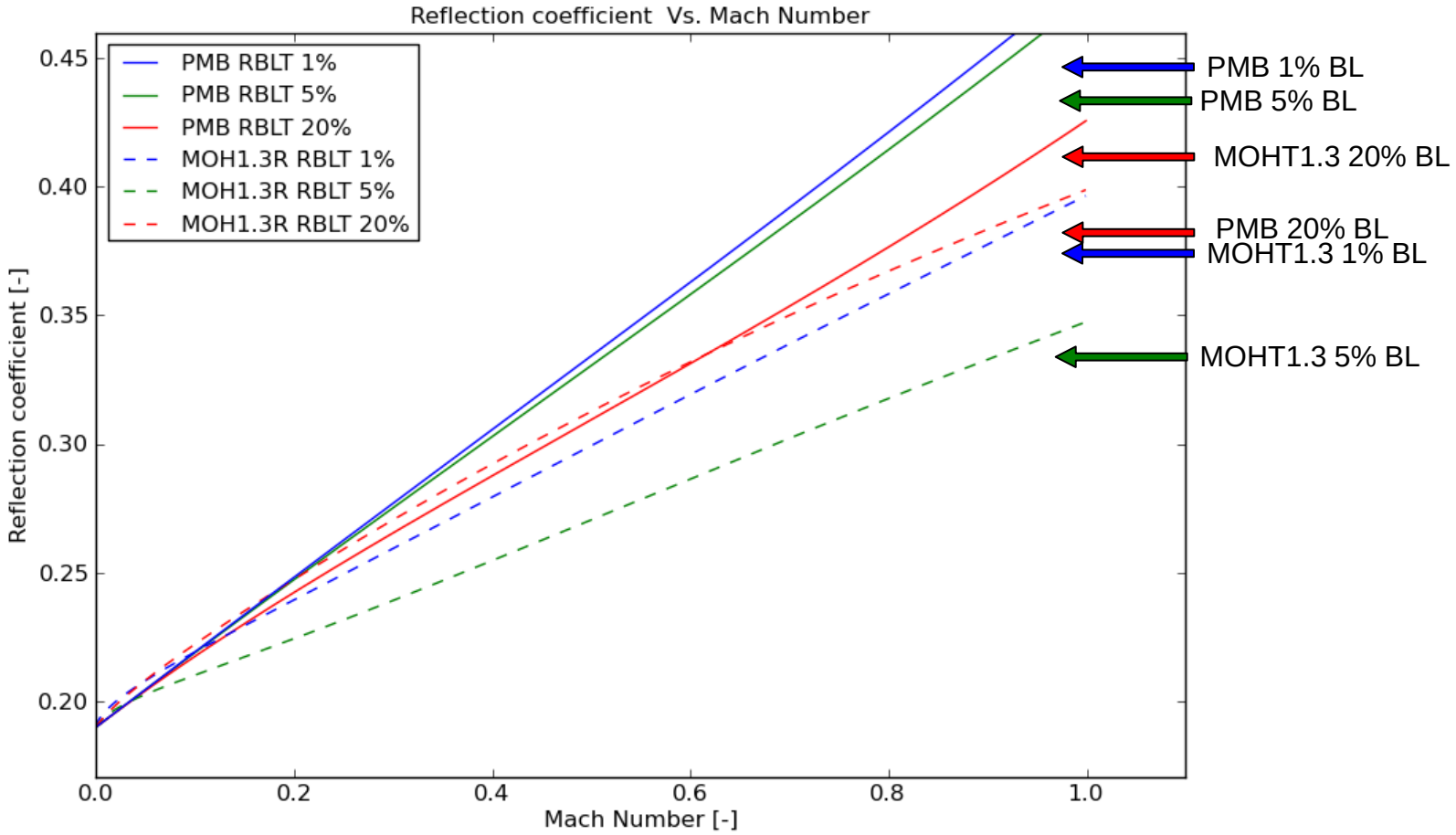
Numerical results (Möhring vs. PMB)

- **New Möhring equation MOH3R:** Reflection coefficient vs. Mach number



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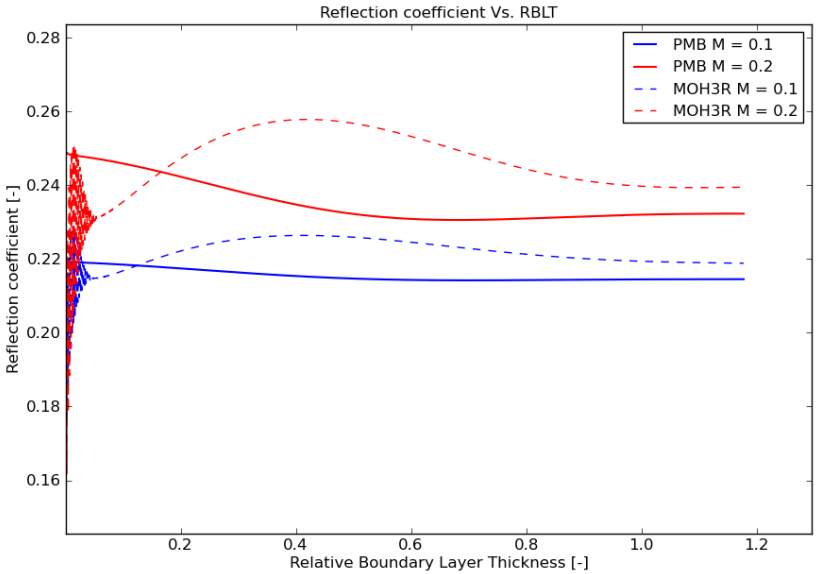
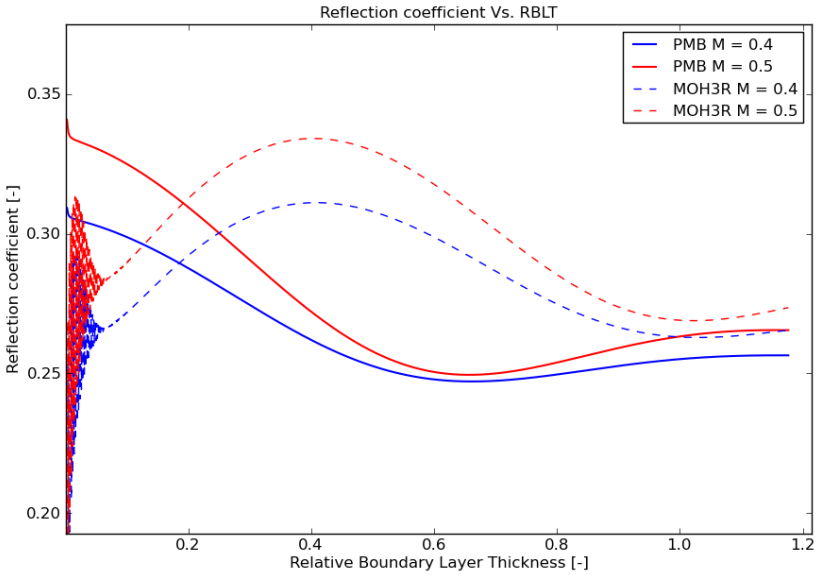
Numerical results (Möhring vs. PMB)

- **New Möhring equation MOH3R:** Reflection coefficient vs. RBLT

Good behaviour at high vorticity





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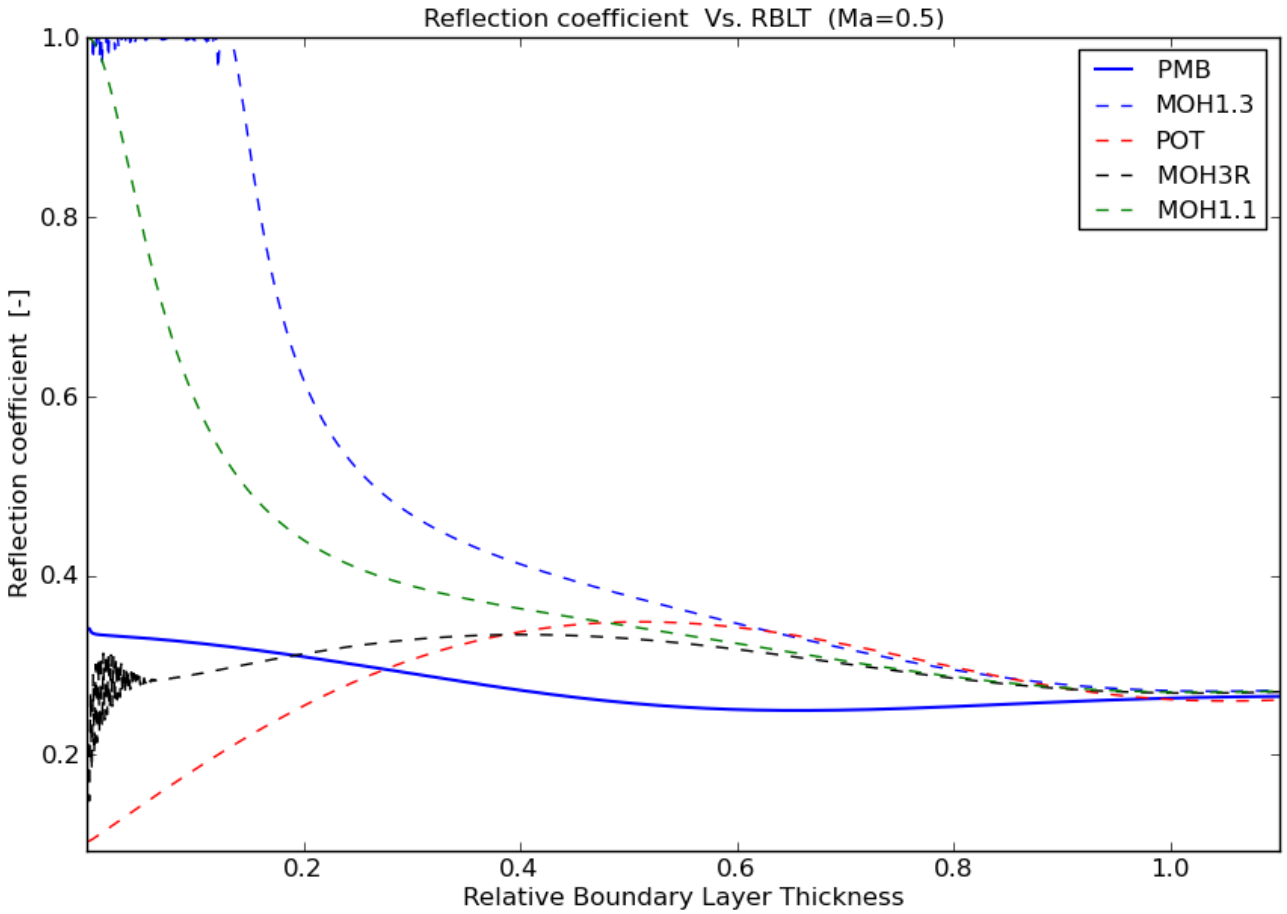
Numerical results (all models)

- Reflection coefficient vs. RBLT:



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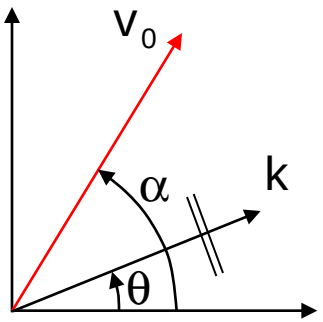
Reducing dispersion errors

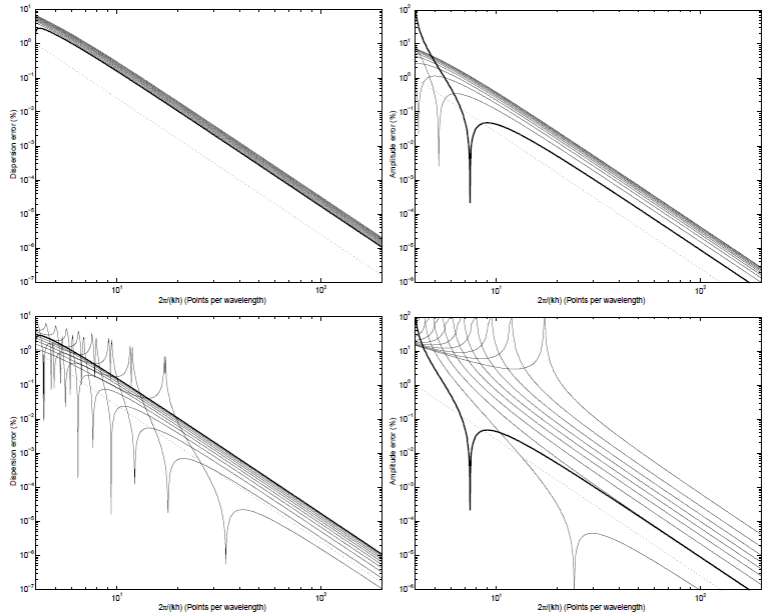
- Dispersion analysis for wave problems:
  - Well established results for standard Helmholz problem (Harari,1997; Babuska et al., 1999, etc)
  - Extension to convected Helmholtz problem is more recent (Astley, Gamallo and Gabard, 2004)

$$k(\alpha,\theta) = \frac{k_0}{1+M\cos(\theta-\alpha)}$$

$$\theta-\alpha = 0 \rightarrow \lambda_d = \lambda_0(1+M)$$

$$\theta-\alpha = \pi \rightarrow \lambda_u = \lambda_0(1-M)$$





← Upstream

← Downstream

Figure 4: Dispersion error E_d (left) and amplitude error E_a (right), in %, for upstream (top) and downstream (bottom) propagation with the L3, Q8 and Q9 elements. Thick solid line: no flow case ($M = 0$); Solid lines: $M = \pm 0.1$ to ± 0.9 by an increment of 0.1. Dotted line: the fourth order slope.

[Astley et al., ECCOMAS, 2004]

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Reducing dispersion errors

- Practical ways for reducing dispersion/pollution errors:

$$\varepsilon_d = \frac{\tilde{k}h - kh}{kh} \qquad |\varepsilon_d| \approx C(kh)^{2p}$$

  - Higher order polynomials: linear → quadratic → cubic → …
    - Preserve robustness
    - Compatibility with mesh generators?
  - Higher order formulations (partition of unity methods):
    - Plane wave enrichment
    - Ill-conditioning issues → loss of robustness
  - Various stabilized formulations …
    - Example: modified integration schemes (Guddati, 2004)
      - Trivial modification for significant improvements
      - Edge effects (compatibility between modified FE and conventional IE)

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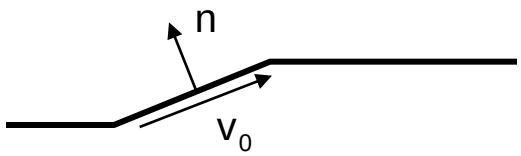
Treatment of Myers bc in a FE context

- Relation between the normal acoustic velocity v_n and the wall displacement u_n in a non-viscous steady flow for harmonic perturbations at frequency ω (Myers):

$$v_n = i\omega u_n + v_0 \cdot \nabla u_n - u_n \, n \cdot (n \cdot \nabla) v_0$$



$$p = i\omega z(\omega) u_n$$

- Acoustic propagation (in a steady potential flow) based on a velocity potential ϕ :

$$p = -\rho_0 (i\omega\phi + v \cdot \nabla\phi) \qquad v = \nabla\phi$$

- Handing of this boundary condition in a FE context:
  - Main difficulty: velocity derivative in Myers bc leads to involve the second order derivative of the potential
  - Regularization proposed by Eversman (JSV, 2001)

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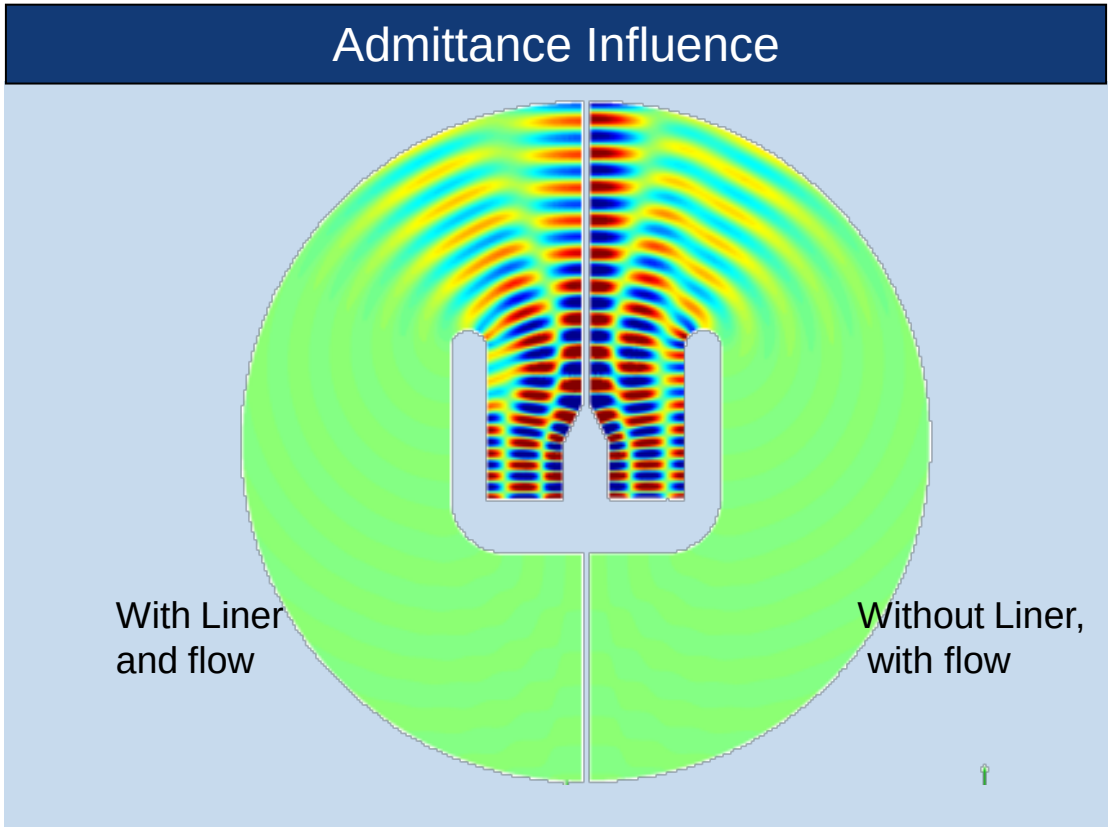
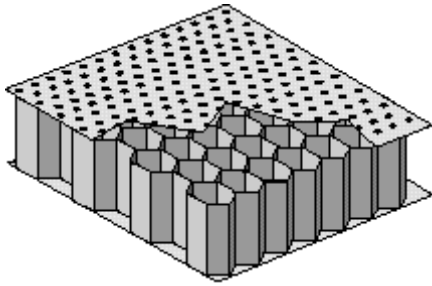
Example / Myers-Eversman boundary condition

- Actran TM incorporates Eversman regularization technique for handling Myers boundary condition
- Evaluation of acoustic attenuation provided by liners for flow/non-flow cases





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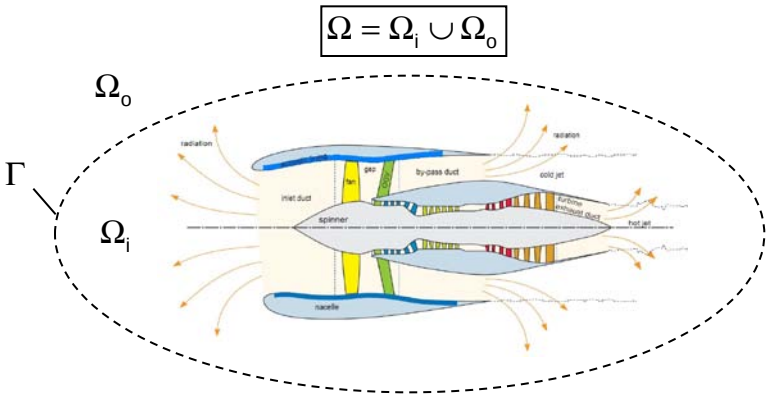
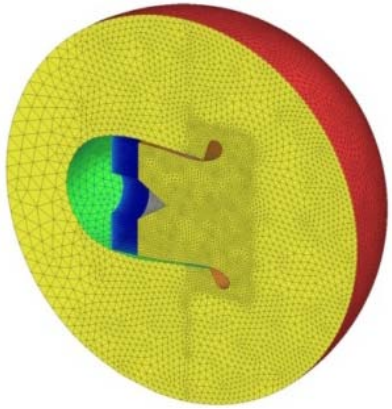
Computational domain

- Handling the external radiation condition in a domain based formulation
- Partition of the propagating domain into inner and outer sub-domains:





- Usual technique for handling the outer sub-domain:
  - Infinite elements (Atley-Leis formulation, uniform flow, higher-order radial interpolation scheme) ← Actran TM
  - Buffer zones (« PML ») ← Actran DGM
- Far field evaluation can rely on boundary integral representations (FWH)

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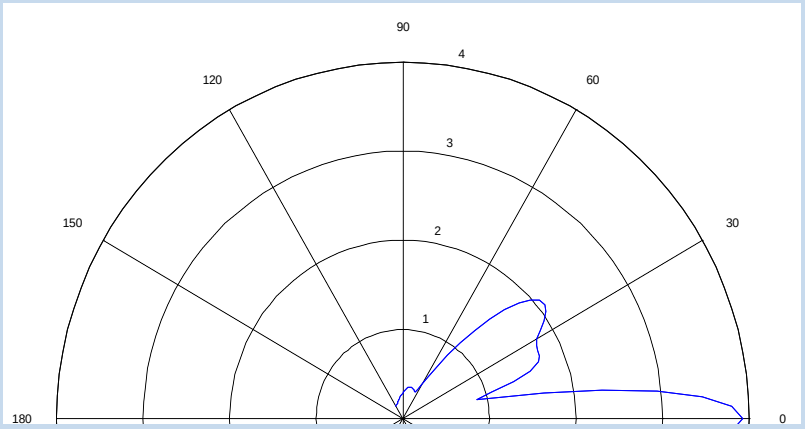
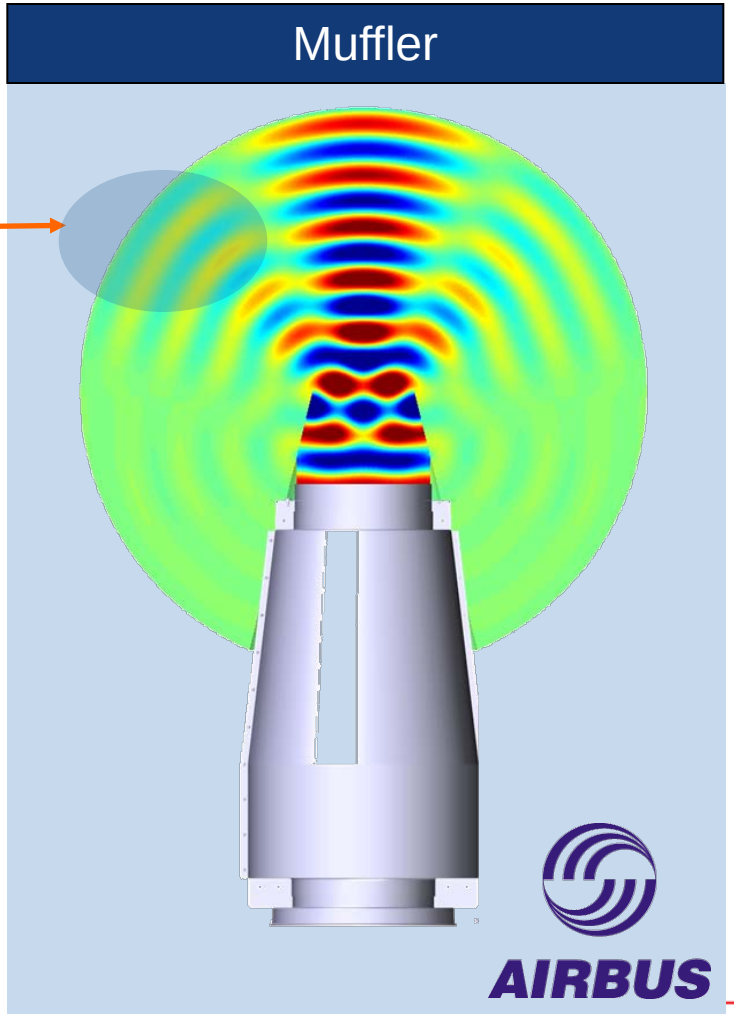
Interest of infinite elements

- Two roles:
  - Act as a non reflective boundary condition (free field modeling)
  - Give access to results outside the inner domain

Directivity Diagram



Muffler



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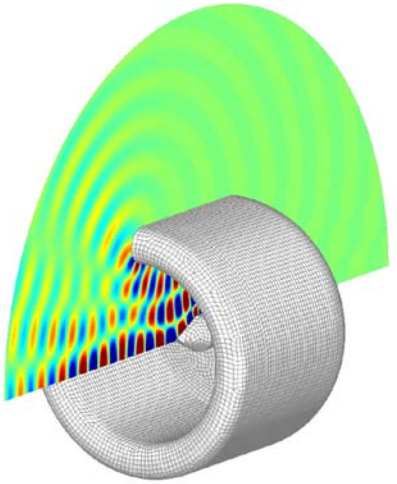
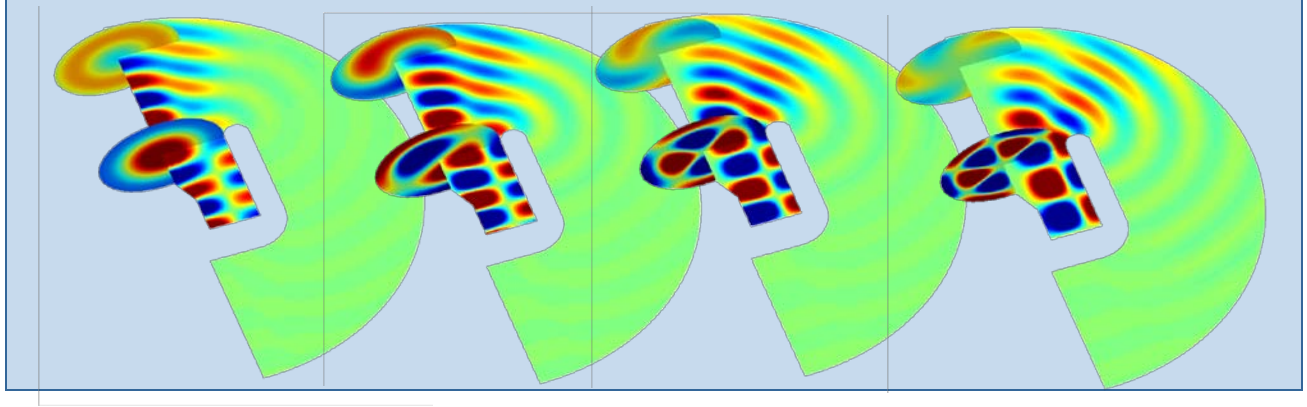
Axisymmetric computations

- Axisymmetry features:
  - 3D results at (almost) the cost of a 2D computation!
  - Meshing is easier
  - Post-processing is faster
  - Sufficient for early design



Results for different azimuthal orders



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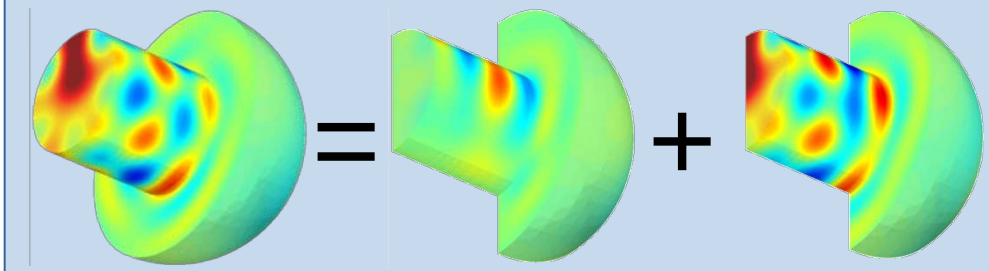
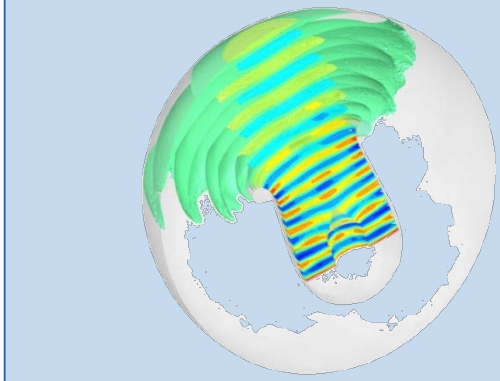
Symmetry & Anti-Symmetry

- Actran can take advantage of spinning modes decomposition:
  - The 2 half models are based on the same mesh → Same pre-processing time than for the complete model
  - Allows both to improve the performances and to perform computations on large size problems
  - Leads to 4 times less CPU & RAM

Symmetric and anti-symmetric decomposition strategy



Computation on a half nacelle



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Modal ducts

- Modal ducts:
  - Acoustic propagation in cylindrical ducts:

$$\Delta_{xy}\phi + \left(1 - M^2\right)\frac{\partial^2\phi}{\partial z^2} - 2ikM\frac{\partial\phi}{\partial z} + k^2 p = 0$$

  - Solution in terms of transverse modes:

$$\phi(x,y,z) = \sum_{m,n} \phi_{mn}(x,y)\left(a^{+}_{mn} e^{-ik^{+}_{zmn} z} + a^{-}_{mn} e^{-ik^{-}_{zmn} z}\right)$$

  - Available cross-section geometries:
    - Circular, annular and rectangular → analytical formulation
    - Arbitrary → numerical formulation
  - Cut-on frequencies related to identified modes
  - Modal intensity
- Coupling FE model with a modal duct component:
  - Mixing physical and modal unknowns in the underlying variational form
  - Possibility to constraint individual modes
  - Driving modes in amplitude or intensity
- Application to broadband fan noise through modal energy equirepartition

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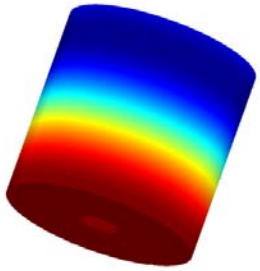
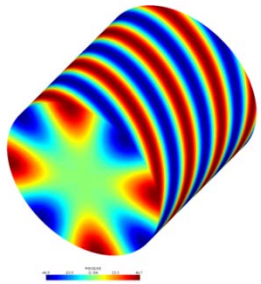
Modeling sources using duct modes

- Source represented by a set of duct modes (Tyler & Sofrin theory)
- These modes are rotating modes characterized by with radial and azimuthal orders
- Selection of constrained modal amplitudes can rely on well established rules
- Reflected modes are let free (non reflecting boundary condition)



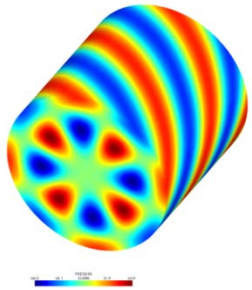
Radial order = 1

Azimuthal order =0



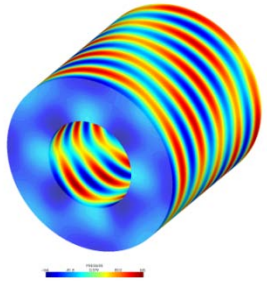
Radial order = 1

Azimuthal order = 4



Radial order = 2

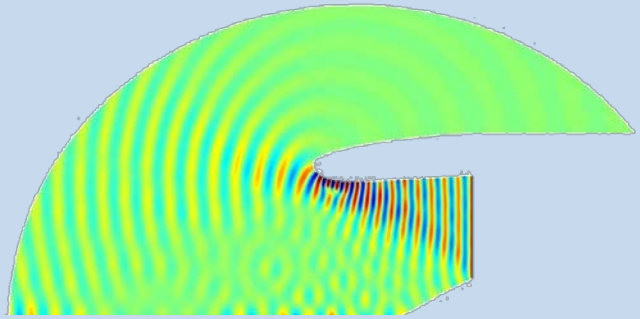
Azimuthal order =4

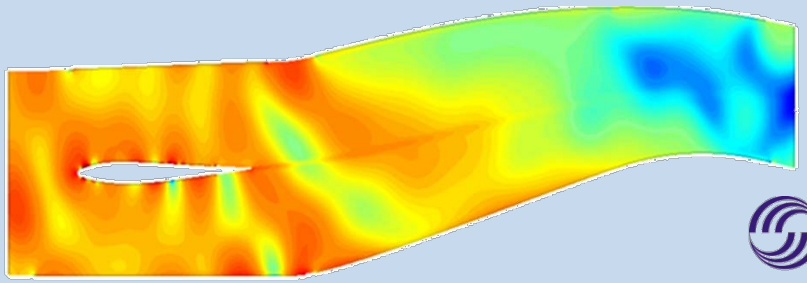


Radial order = 3

Azimuthal order =4

Axisymmetric Nacelle & Splitter in a Bypass





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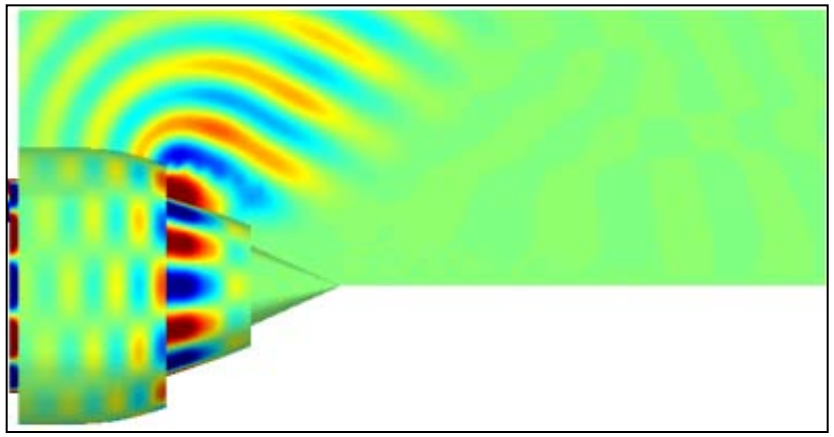
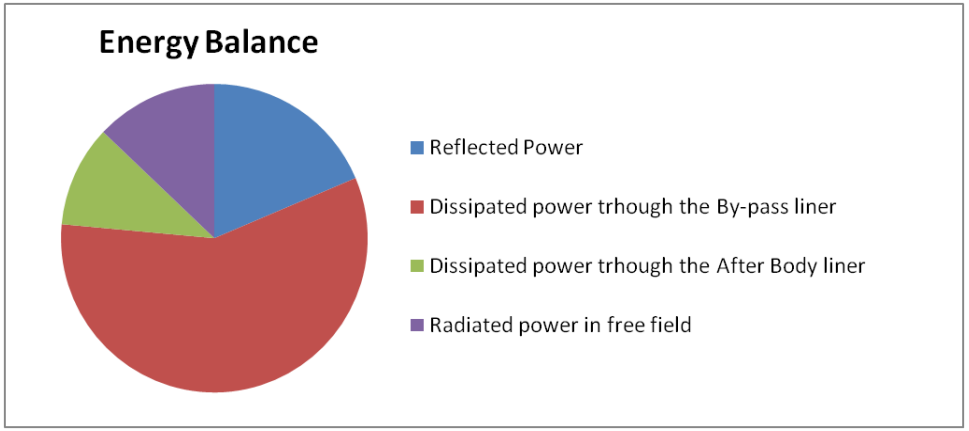
Capability to produce relevant indicators

- Output maps for near field and far field
- Directivity diagrams
- Energy indicators → energy balance of the system





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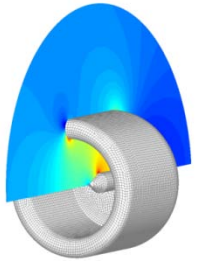
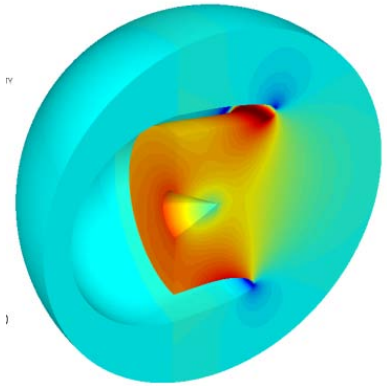
Handling the mean Flow

- Actran TM can handle heterogeneous mean flow
- A compressible potential flow calculation can be performed
- Alternative: use an external CFD code
  - Coupling with Star-CD, Fluent and other proprietary codes
  - Procedure:



CFD → Actran → Flow interpolated on Actran mesh

CD-adapco FLUENT



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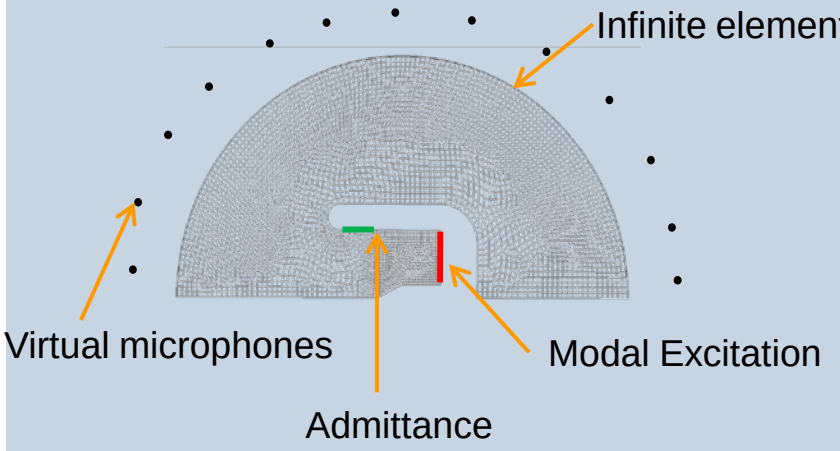
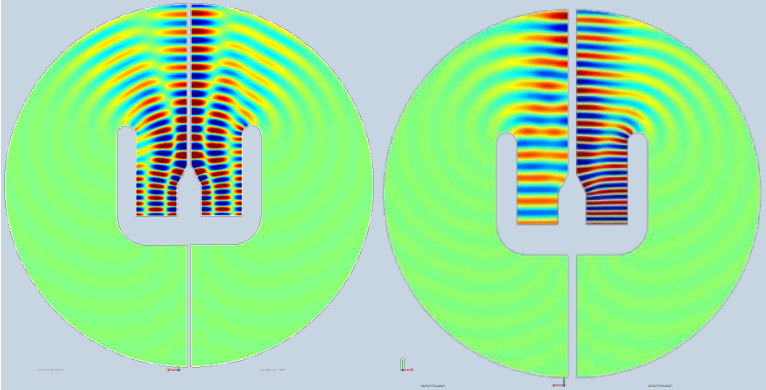
Case Study: Nacelle Inlet

ACTRAN model



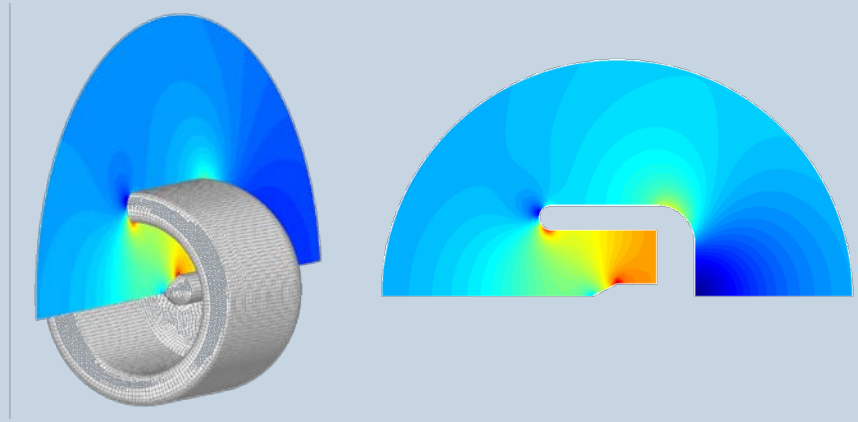
Results

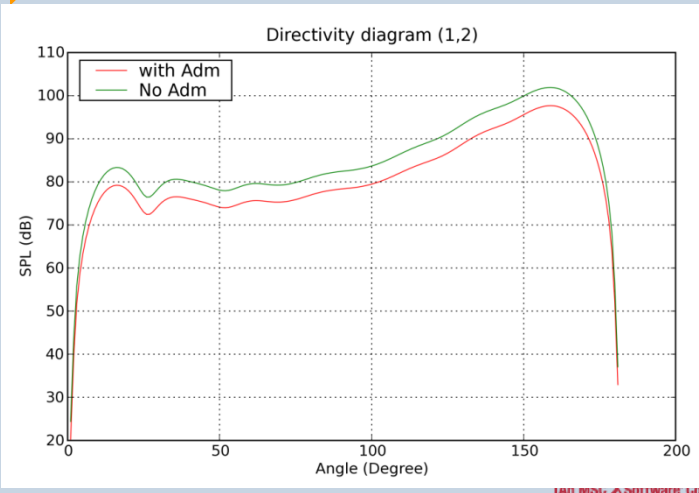


Liner influence

Mean flow influence

Mean flow computed with ACTRAN





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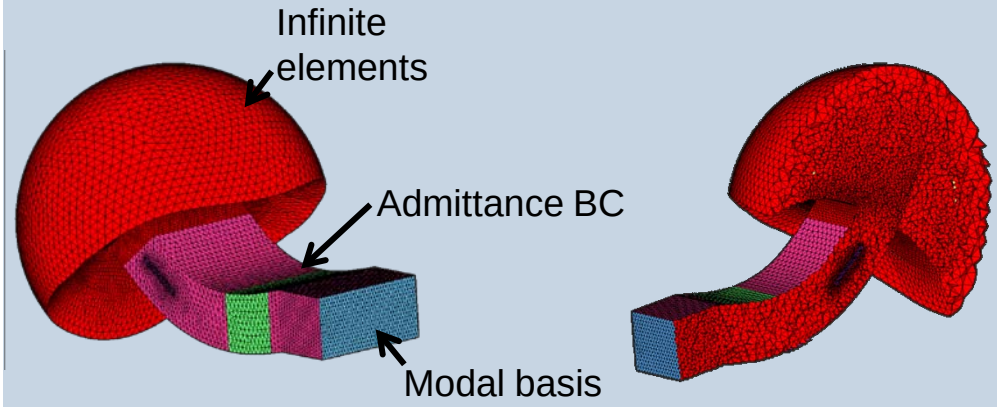
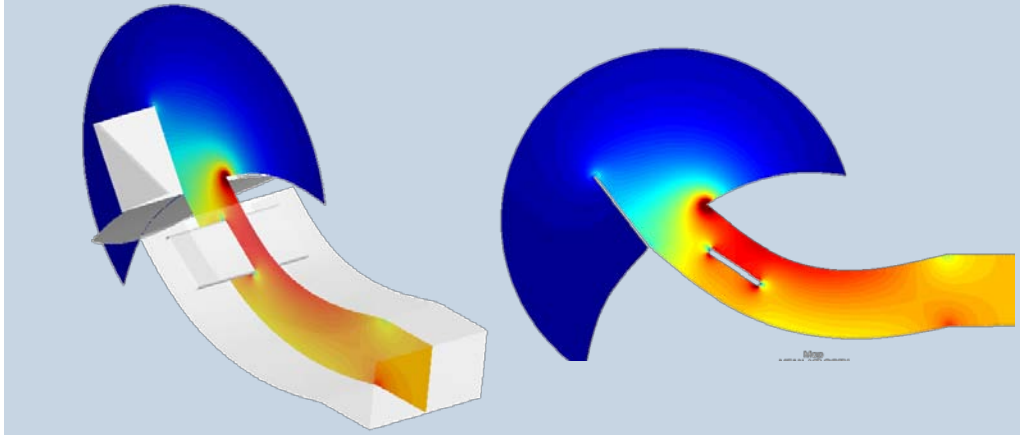
Case Study: APU

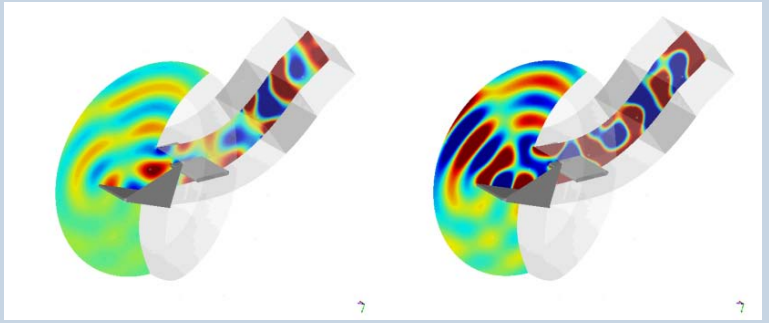
ACTRAN Model

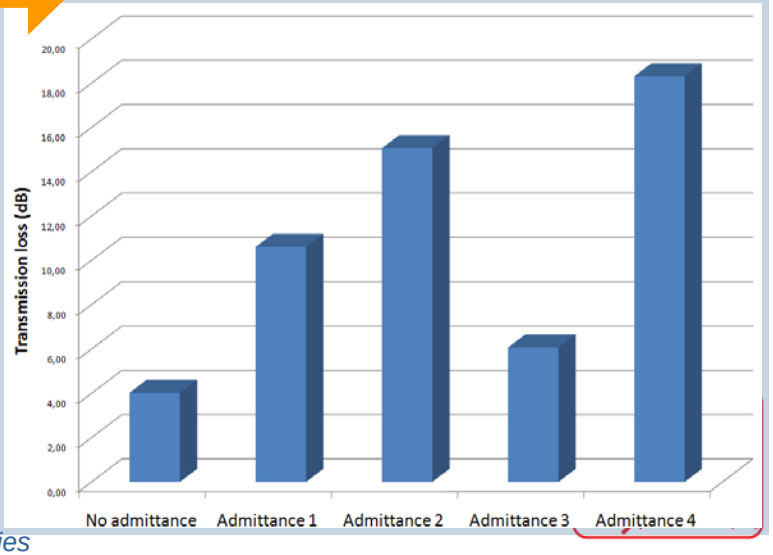


Mean flow computed by Fluent



Results





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Experimental validations

- Many investigators have performed experimental validations
- Some earlier works:
  - ”Fan Noise Radiation from Intake: Comparisons between FEM Prediction and Fan Rig Test Measurements with Flare”, S.Lidoine & B.Caruelle, ICSV 2005

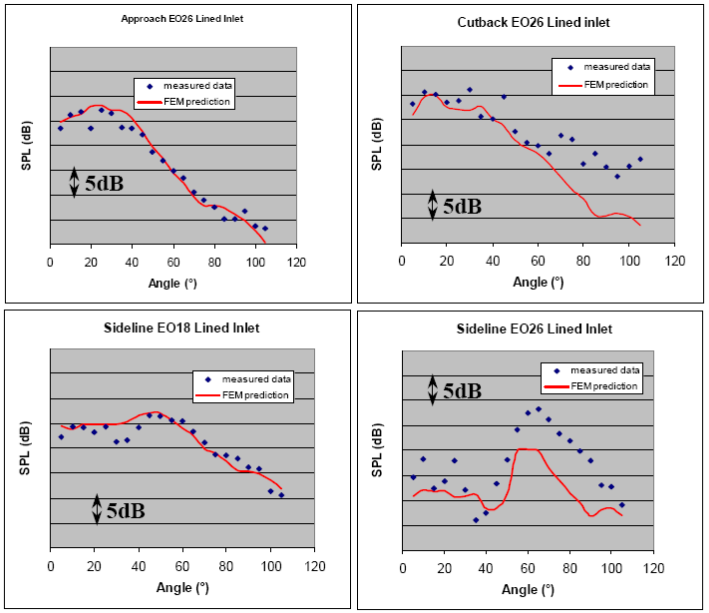

Figure 6 – Comparisons between measured data and ACTRAN prediction, Lined inlet case.

- “Development and validation of a parallel out-of-core propagation and radiation code with validation on a turbofan application”, P.Ploumhans et al, ICA 2004-702

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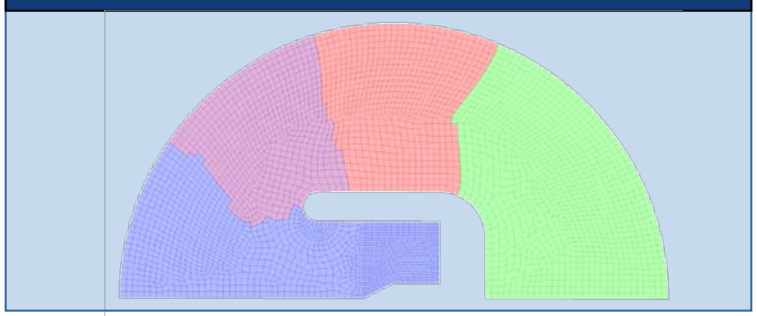
Parallelisms & Multi-Loadcase

- Domain parallelism
  - Improves the computation performances (scalability)
  - Allows to perform computations on large models
  - Automatic optimized partitioning
- Frequency parallelism
  - Computations at several frequencies are performed at the same time
  - (Perfect) scalability
- Multi-loadcase capability
  - All modal responses computed in one computation
  - Mandatory for broadband computations

Optimized partitioning for an axisymmetric nacelle



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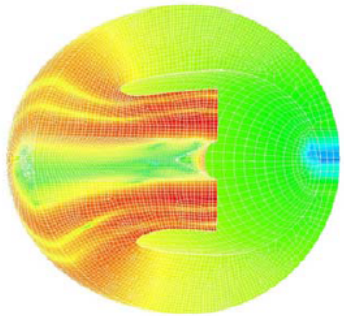
Solver efficiency

- Airbus tests (A. Mosson, User's meeting, 2010):

Radiating Inlets with ACTRAN/TM

- Objectives
  - To define optimal run parameters
  - To evaluate the highest frequency reachable on our clusters
- Release
  - Actran_10.0
- Description
  - A380 T900 3D inlet
  - 3 different ½ models
  - Hybrid mesh (hexa, pyra, penta, tetra)
  - Broad band calculation
- Run parameters
  - MPI parallelism
  - Multithreading
  - In/out-of core MUMPS solver
  - Right Hand Side (RHS) Block Size

Frequency	0.5 bpf	1 bpf	2 bpf
Kdofs	412	2059	7047
Cut-on modes	41	147	578



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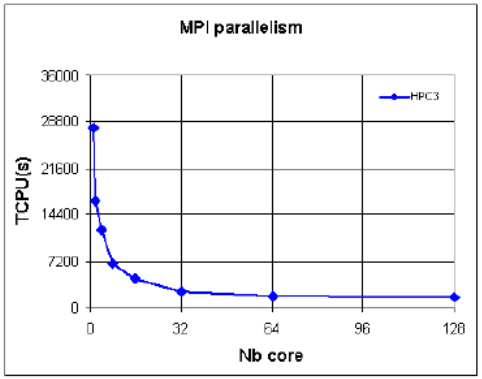
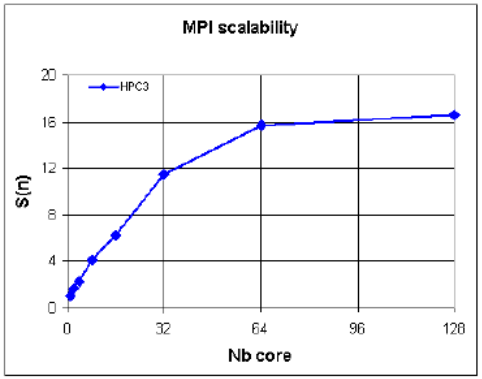
Solver efficiency

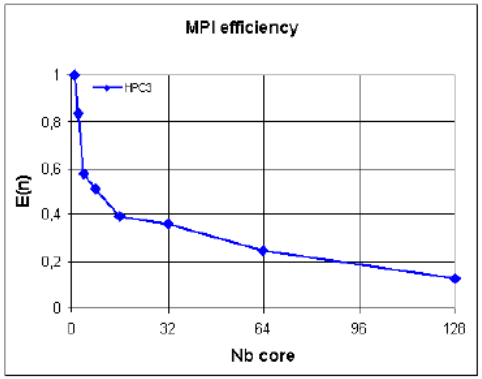
- Airbus tests (A. Mosson, User's meeting, 2010):

MPI Parallelism and Multithreading Efficiency

- MPI parallelism
  - 1bpf model
  - In-core MUMPS Solver
  - Single load simulation







- Interesting scalability up to 64 cores
- The efficiency remains quite good up to 32 cores

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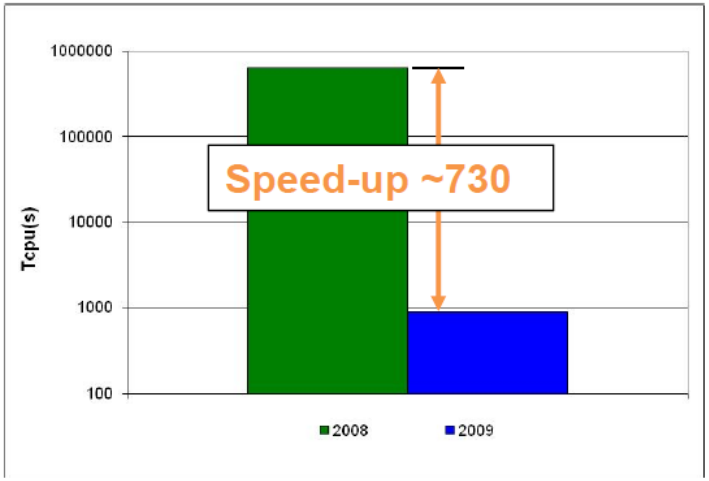
Solver efficiency

- Airbus tests (A. Mosson, User's meeting, 2010):

Improvement since 2008

- 1bpf model – Single load simulation



- Power 5+ to Nehalem architecture ⇒ **Speed-up ~ 2.5**
- SPARSE to MUMPS solver ⇒ **Speed-up ~ 9**
- Optimal parallelism 32 mpi x 4 threads ⇒ **Speed-up ~ 32**

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Conclusions

- Overview of key ingredients for modeling flow acoustic problems:
  - Availability of various propagation models
  - Modeling liners and handling shear layer effects
  - Exterior acoustics for domain based formulations
  - Modal coupling for handling excitations
  - Relevant output indicators
  - Performance issues:
    - Axi-symmetric vs. 3D models
    - Symmetric/anti-symmetric decomposition
    - Parallelism
    - Solver efficiency

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Challenges

- Establish links between sub-models (example: DNS for $z(\omega)$ → CWE for response)
- Develop and implement criteria to secure the selection of appropriate reduced models
- Develop and implement a posteriori error indicators
- Develop robust higher-order formulations for the short wave problem
- Investigate appropriate strategies for modeling bulk reacting liners
- Improve solver performances (a continuous process!)

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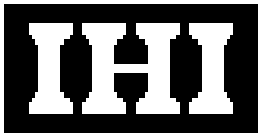
Thanks to our customers!



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