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Asymptotic Models for an Elasto-Acoustic Problem with a Thin Layer

VICTOR PÉRON

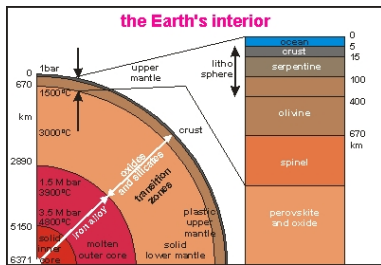
Université de Pau et des Pays de l'Adour
INRIA Bordeaux Sud-Ouest, Team MAGIQUE 3D

Twelfth International Conference Zaragoza-Pau on Mathematics
Jaca, September 17, 2012

Motivations

HPC-GA Project

- **High Performance Computing for Geophysics Applications :**
Earthquakes
- **Numerical Models :** Time dependent Elasto-Acoustic Coupling
 - Elasto-Acoustic Coupling : to reproduce earthquakes
 - Modeling the effects of the ocean on seismic waves

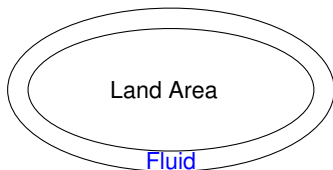


- The medium : a Land Area surrounded by a **thin Fluid zone**

Motivations

Configuration, Difficulty and Method

- **Configuration**



- **Difficulty**

Apply a FEM on a mesh with **thin cells** in the **Fluid** and much larger in the solid

- **Method**

- 1 Replace the **Fluid layer** by an Equivalent boundary condition

Approach : an asymptotic method

- 2 Couple this condition with the elastic wave equation
- 3 Use a FEM



Motivations

Bibliography and Outline

Bibliography

- Modeling Fluid-Solid Interaction Problems
JONES 83, LUKE-MARTIN 95, NATROCHVILI ET AL. 00, ... ,
MONK-SELGAS 09
- Derivation of Equivalent Conditions for **thin layer** Problems
LAFITTE 93, ENGQUIST-NÉDÉLEC 93, VOLAKIS-SENIOR 95,
BENDALI-LEMRAËT 96, CALOZ-COSTABEL-DAUGE-VIAL 06 ...

Outline

- Asymptotic Analysis for the time-harmonic **Elasto-acoustic** equations in a domain with a **thin acoustic layer**.

Outline

- 1 **Uniform Estimates**
- 2 Equivalent Conditions
- 3 Numerical Simulations

An Elasto-Acoustic Problem with a Thin Layer

Framework and Issue

The Problem (\mathbf{P}_ϵ) set in a smooth bounded domain $\Omega^\epsilon = \Omega_s \cup \Gamma \cup \Omega_f^\epsilon$:

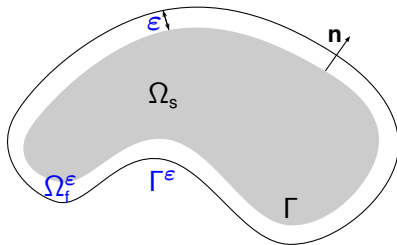
$$\Delta p + \kappa^2 p = 0 \quad \text{in } \Omega_f^\epsilon$$

$$\nabla \cdot \underline{C}(x) \nabla \mathbf{u} + \omega^2 \rho \mathbf{u} = 0 \quad \text{in } \Omega_s$$

$$\partial_n p = \rho_f \omega^2 \mathbf{u} \cdot \mathbf{n} - \partial_n p_i \quad \text{on } \Gamma$$

$$\mathbf{n} \underline{C}(x) \nabla \mathbf{u} = -p \mathbf{n} - p_i \mathbf{n} \quad \text{on } \Gamma$$

$$p = 0 \quad \text{on } \Gamma^\epsilon$$



Assumption

(i) $\underline{C}(x) = (C_{ijkl}(x))$ is symmetric : $C_{ijkl} = C_{jikl} = C_{klij}$.

(ii) $C_{ijkl}(x)$ are real valued smooth functions, up to Γ .

(iii) $\exists \alpha > 0, \quad \forall \xi = (\xi_{ij})$ sym. tensor, $\sum_{i,j,k,l} C_{ijkl} \xi_{ij} \bar{\xi}_{kl} \geq \alpha \sum_{i,j} |\xi_{ij}|^2$.

Weak Solutions

Variational Problem $(VP)_\varepsilon$

- $V_\varepsilon = \{(\mathbf{u}, p) \in H^1(\Omega_s) \times H^1(\Omega_f^\varepsilon) \mid \gamma_0 p = 0 \text{ on } \Gamma^\varepsilon\}$
- For all $\varepsilon > 0$, $(VP)_\varepsilon$ writes : Find $(\mathbf{u}_\varepsilon, p_\varepsilon) \in V_\varepsilon$ such that

$$\forall (\mathbf{v}, q) \in V_\varepsilon, \quad a_\varepsilon((\mathbf{u}_\varepsilon, p_\varepsilon), (\mathbf{v}, q)) = \langle F, (\mathbf{v}, q) \rangle_{V_\varepsilon', V_\varepsilon}$$

$$a_\varepsilon((\mathbf{u}, p), (\mathbf{v}, q)) := \int_{\Omega_f^\varepsilon} (\nabla p \cdot \nabla \bar{q} - \kappa^2 p \bar{q}) \, d\mathbf{x}$$

$$+ \int_{\Omega_s} (\underline{C}(\mathbf{x}) \underline{\nabla} \mathbf{u} : \underline{\nabla} \bar{\mathbf{v}} - \omega^2 \rho \mathbf{u} \bar{\mathbf{v}}) \, d\mathbf{x} + \int_\Gamma (\omega^2 \rho_f \mathbf{u} \cdot \mathbf{n} \bar{q} + p \bar{\mathbf{v}} \cdot \mathbf{n}) \, ds$$

Uniform Estimates

Some resonant frequencies may appear in the solid

Assumption (SA)

The angular frequency ω is not an eigenfrequency of the problem

$$\begin{cases} \nabla \cdot \underline{C}(x) \underline{\nabla} \mathbf{u} + \omega^2 \rho \mathbf{u} = 0 & \text{in } \Omega_s \\ \underline{C}(x) \underline{\nabla} \mathbf{u} \mathbf{n} = 0 & \text{on } \Gamma. \end{cases}$$

Theorem

Under Assumption (SA), $\exists \varepsilon_0 > 0, \forall \varepsilon \in (0, \varepsilon_0)$, the problem $(\mathbf{VP})_\varepsilon$ with data $F \in V'_\varepsilon$ has a unique solution $(\mathbf{u}_\varepsilon, \mathbf{p}_\varepsilon) \in V_\varepsilon$ and

$$\|\mathbf{u}_\varepsilon\|_{1, \Omega_s} + \|\mathbf{p}_\varepsilon\|_{1, \Omega_\varepsilon} \leq C \|F\|_{V'_\varepsilon}.$$

Application : Convergence of an asymptotic expansion as $\varepsilon \rightarrow 0$.

Key for the proof: introduce a "Scaled Problem"

Scaled Problem $(\mathfrak{P})_\epsilon$

Formulation in a fixed domain

- For any function p defined in Ω_f^ϵ , define \mathfrak{p} in $\Omega_f := \Gamma \times (0, 1)$:

$$\mathfrak{p}(\mathbf{x}) = p(\Psi(y_\alpha), S), \quad S = \frac{s}{\epsilon} \in (0, 1).$$

- $V = \{(\mathbf{u}, p) \in H^1(\Omega_s) \times H^1(\Omega_f) \mid p(\cdot, 1) = 0 \text{ on } \Gamma\}$
- $(\mathfrak{P})_\epsilon$ writes : Find $(\mathbf{u}, p) \in V$ such that $\forall (\mathbf{v}, q) \in V$

$$\begin{aligned} \epsilon \int_0^1 \int_\Gamma [(\mathbb{I} + \epsilon S \mathcal{R})^{-2} \nabla_\Gamma \mathfrak{p} \nabla_\Gamma \bar{q} + \epsilon^{-2} \partial_s \mathfrak{p} \partial_s \bar{q} - \kappa^2 \mathfrak{p} \bar{q}] \det(\mathbb{I} + \epsilon S \mathcal{R}) \, d\Omega_f \\ + a_s(\mathbf{u}, \mathbf{v}) + \int_\Gamma (\omega^2 \rho_f \mathbf{u} \cdot \mathbf{n} \bar{q} + \mathfrak{p} \bar{\mathbf{v}} \cdot \mathbf{n}) \, d\Gamma = \langle \mathfrak{F}_\epsilon, (\mathbf{v}, q) \rangle_{V', V} \end{aligned}$$

Scaled Problem $(\mathfrak{P})_\varepsilon$

Uniform estimates

Lemma

Under Assumption (SA), $\exists \varepsilon_0 > 0$, $\forall \varepsilon \in (0, \varepsilon_0)$, any solution $(\mathbf{u}_\varepsilon, \mathbf{p}_\varepsilon) \in V$ of problem $(\mathfrak{P})_\varepsilon$ with a data $\mathfrak{F}_\varepsilon \in V'$ satisfies

$$\|(\mathbf{u}_\varepsilon, \mathbf{p}_\varepsilon)\|_{0, \Omega_s \times \Omega_f} + \|\mathbf{u}_\varepsilon \cdot \mathbf{n}\|_{0, \Gamma} + \|\mathbf{p}_\varepsilon\|_{0, \Gamma} \leq C \|\mathfrak{F}_\varepsilon\|_{V'}.$$

Theorem

Under Assumption (SA), $\exists \varepsilon_0 > 0$, $\forall \varepsilon \in (0, \varepsilon_0)$, the problem $(\mathfrak{P})_\varepsilon$ with data $\mathfrak{F}_\varepsilon \in V'$ has a unique solution $(\mathbf{u}_\varepsilon, \mathbf{p}_\varepsilon) \in V$ which satisfies

$$\sqrt{\varepsilon} \|\nabla_\Gamma \mathbf{p}_\varepsilon\|_{0, \Omega_f} + \sqrt{\varepsilon}^{-1} \|\partial_S \mathbf{p}_\varepsilon\|_{0, \Omega_f} + \|\mathbf{p}_\varepsilon\|_{0, \Omega_f} + \|\mathbf{u}_\varepsilon\|_{1, \Omega_s} \leq C \|\mathfrak{F}_\varepsilon\|_{V'}.$$

Sketch of the proof of the Lemma

Proof by contradiction.

Assume : $\exists(\mathbf{u}_m, \mathbf{p}_m) \in V, m \in \mathbb{N}$, satisfying $(\mathfrak{B})_{\epsilon_m}$ associated with $\epsilon_m \rightarrow 0$ and $\tilde{\mathfrak{F}}_m \in V'$ such that

$$\|(\mathbf{u}_m, \mathbf{p}_m)\|_{0, \Omega_s \times \Omega_f} + \|\mathbf{u}_m \cdot \mathbf{n}\|_{0, \Gamma} + \|\mathbf{p}_m\|_{0, \Gamma} = 1 \quad \text{and} \quad \|\tilde{\mathfrak{F}}_m\|_{V'} \rightarrow 0$$

- 1 Prove that $\|(\mathbf{u}_m, \mathbf{p}_m)\|_W \leq C$
 with $W = \{(\mathbf{u}, \mathbf{p}) \in V \mid \mathbf{p} \in \mathbf{H}^1(0, 1; L^2(\Gamma)), \mathbf{p}(\cdot, 1) = 0 \text{ on } \Gamma\}$
- 2 Compactness argument :
 $\mathbf{u}_m \rightarrow \mathbf{u}$ in $L^2(\Omega_s)$ and $\mathbf{p}_m \rightarrow \mathbf{p} = 0$ in $L^2(\Omega_f)$.
- 3 Prove that $\|\mathbf{u}\|_{0, \Omega_s} + \|\mathbf{u} \cdot \mathbf{n}\|_{0, \Gamma} = 1$
- 4 Using (SA), we prove $\mathbf{u} = 0$: contradiction

Outline

- 1 Uniform Estimates
- 2 Equivalent Conditions**
- 3 Numerical Simulations

Methodology

Framework : $\Gamma, \Gamma^\varepsilon$ smooth surfaces in \mathbb{R}^3 . Smooth data

- Step 1 : Derive an Asymptotic Expansion for $(\mathbf{u}_\varepsilon, p_\varepsilon)$ when $\varepsilon \rightarrow 0$

$$\mathbf{u}_\varepsilon(x) = \mathbf{u}_0(x) + \varepsilon \mathbf{u}_1(x) + \varepsilon^2 \mathbf{u}_2(x) + \dots,$$

$$p_\varepsilon(x) = p_0(x; \varepsilon) + \varepsilon p_1(x; \varepsilon) + \varepsilon^2 p_2(x; \varepsilon) + \dots, \quad p_j(x; \varepsilon) = p_j(y_\alpha, \frac{S}{\varepsilon}).$$

- Step 2 : Derive Equivalent Conditions of order $k \in \mathbb{N}$:
Identify a simpler problem satisfied by

$$\mathbf{u}_{k,\varepsilon} := \mathbf{u}_0 + \varepsilon \mathbf{u}_1 + \varepsilon^2 \mathbf{u}_2 + \dots + \varepsilon^k \mathbf{u}_k \quad \text{up to } \mathcal{O}(\varepsilon^{k+1})$$

- Step 3 : Prove the Stability of Equivalent models \mathbf{u}_ε^k and

$$\|\mathbf{u}_\varepsilon - \mathbf{u}_\varepsilon^k\|_{1,\Omega_s} \leq C\varepsilon^{k+1}$$

Step 1 : Multiscale Expansion

First terms

- At step $n = 0$, we obtain

$$p_0 = 0 ,$$

and then \mathbf{u}_0 solves the problem

$$\begin{cases} \nabla \cdot \underline{\underline{C}}(x) \nabla \mathbf{u}_0 + \omega^2 \rho \mathbf{u}_0 = 0 & \text{in } \Omega_s \\ \mathbf{T}(\mathbf{u}_0) = -p_i \mathbf{n} & \text{on } \Gamma . \end{cases}$$

- At step $n = 1$, we find successively

$$p_1(\cdot, S) = (S - 1) (\rho_f \omega^2 \mathbf{u}_0 \cdot \mathbf{n} - \partial_n p_i) , \quad S \in (0, 1)$$

and that \mathbf{u}_1 solves

$$\begin{cases} \nabla \cdot \underline{\underline{C}}(x) \nabla \mathbf{u}_1 + \omega^2 \rho \mathbf{u}_1 = 0 & \text{in } \Omega_s \\ \mathbf{T}(\mathbf{u}_1) = \rho_f \omega^2 \mathbf{u}_0 \cdot \mathbf{n} \mathbf{n} - \partial_n p_i \mathbf{n} & \text{on } \Gamma . \end{cases}$$

Step 1 : Multiscale Expansion

First terms

- At step $n = 2$,

$$p_2(\cdot, Y_3) = (S^2 - 1)\mathcal{H}[\rho_f \omega^2 \mathbf{u}_0 \cdot \mathbf{n} - \partial_n p_i] + (S - 1)\rho_f \omega^2 \mathbf{u}_1 \cdot \mathbf{n}$$

and then, \mathbf{u}_2 solves

$$\begin{cases} \nabla \cdot \underline{C}(x) \nabla \mathbf{u}_2 + \omega^2 \rho \mathbf{u}_2 = 0 & \text{in } \Omega_s \\ \mathbf{T}(\mathbf{u}_2) = \rho_f \omega^2 \mathbf{u}_1 \cdot \mathbf{n} \mathbf{n} + \mathcal{H}[\rho_f \omega^2 \mathbf{u}_0 \cdot \mathbf{n} - \partial_n p_i] \mathbf{n} & \text{on } \Gamma. \end{cases}$$

Step 1 : Validation of the Asymptotic Expansion

Aim : proving Estimates for Remainders

$$\mathbf{r}_\epsilon^{N+1} := \mathbf{u}_\epsilon - \sum_{n=0}^N \epsilon^n \mathbf{u}_n \quad \text{in } \Omega_s, \quad \text{and} \quad r_\epsilon^{N+1} := p_\epsilon - \sum_{n=0}^N \epsilon^n p_n \quad \text{in } \Omega_f^\epsilon$$

Evaluation of the right hand sides in

$$\left\{ \begin{array}{ll} \kappa^2 r_\epsilon^{N+1} + \Delta r_\epsilon^{N+1} & = f_\epsilon \quad \text{in } \Omega_f^\epsilon \\ \omega^2 \rho r_\epsilon^{N+1} + \nabla \cdot \underline{C}(x) \nabla r_\epsilon^{N+1} & = 0 \quad \text{in } \Omega_s \\ \partial_{\mathbf{n}} r_\epsilon^{N+1} - \rho_f \omega^2 r_\epsilon^{N+1} \cdot \mathbf{n} & = g_\epsilon \quad \text{on } \Gamma \\ \mathbf{T}(r_\epsilon^{N+1}) + r_\epsilon^{N+1} \mathbf{n} & = 0 \quad \text{on } \Gamma \\ r_\epsilon^{N+1} & = 0 \quad \text{on } \Gamma^\epsilon. \end{array} \right.$$

The RHS are explicit: $f_\epsilon = \mathcal{O}(\epsilon^{N-\frac{1}{2}})$ in Ω_f^ϵ ; $g_\epsilon = \mathcal{O}(\epsilon^N)$ on Γ

Optimal Estimates : $\|\mathbf{r}_\epsilon^{N+1}\|_{1,\Omega_s} + \sqrt{\epsilon} \|r_\epsilon^{N+1}\|_{1,\Omega_f^\epsilon} \leq C_N \epsilon^{N+1}$

Step 2 : Equivalent Conditions on Γ

Identify a simpler problem

$$(\mathbf{P}_\varepsilon^k) \quad \begin{cases} \omega^2 \rho \mathbf{u}_\varepsilon^k + \nabla \cdot \underline{C}(x) \underline{\nabla} \mathbf{u}_\varepsilon^k = 0 & \text{in } \Omega_s \\ \mathbf{T}(\mathbf{u}_\varepsilon^k) + \mathbf{B}_{k,\varepsilon}(\mathbf{u}_\varepsilon^k) = \mathbf{h}_{k,\varepsilon} & \text{on } \Gamma, \end{cases}$$

with $\mathbf{B}_{k,\varepsilon}$ a surfacic differential operator.

- $k \in \{0, 1, 2\}$ for a Dirichlet b.c. on Γ^ε
- $k \in \{0, 1\}$ for a Fourier-Robin b.c. on Γ^ε

Step 2 : Equivalent Conditions

Dirichlet b.c.

- $k = 0$:

$$\mathbf{T}(\mathbf{u}_0) = -p_i \mathbf{n} \quad \text{on } \Gamma .$$

- $k = 1$:

$$\mathbf{T}(\mathbf{u}_\epsilon^1) - \epsilon \omega^2 \rho_f \mathbf{u}_\epsilon^1 \cdot \mathbf{n} \mathbf{n} = \mathbf{h}_{1,\epsilon} \quad \text{on } \Gamma .$$

- $k = 2$:

$$\mathbf{T}(\mathbf{u}_\epsilon^2) - \epsilon \omega^2 \rho_f (1 + \epsilon \mathcal{H}) \mathbf{u}_\epsilon^2 \cdot \mathbf{n} \mathbf{n} = \mathbf{h}_{2,\epsilon} \quad \text{on } \Gamma .$$

Step 2 : Equivalent Conditions

Example : Order 1

$\mathbf{u}_{1,\varepsilon} = \mathbf{u}_0 + \varepsilon \mathbf{u}_1$ satisfies the elastic equation in Ω_s and

$$\mathbf{T}(\mathbf{u}_{1,\varepsilon}) - \varepsilon \omega^2 \rho_f \mathbf{u}_{1,\varepsilon} \cdot \mathbf{n} \mathbf{n} = -\mathbf{p}_i \mathbf{n} - \varepsilon \partial_n \mathbf{p}_i \mathbf{n} - \varepsilon^2 \rho_f \omega^2 \mathbf{u}_1 \cdot \mathbf{n} \mathbf{n} \quad \text{on } \Gamma$$

We infer a simpler problem

$$(\mathbf{P}_\varepsilon^1) \quad \begin{cases} \omega^2 \rho \mathbf{u}_\varepsilon^1 + \nabla \cdot \underline{\mathbf{C}}(x) \underline{\nabla} \mathbf{u}_\varepsilon^1 = 0 & \text{in } \Omega_s \\ \mathbf{T}(\mathbf{u}_\varepsilon^1) - \varepsilon \omega^2 \rho_f \mathbf{u}_\varepsilon^1 \cdot \mathbf{n} \mathbf{n} = \mathbf{h}_{1,\varepsilon} & \text{on } \Gamma, \end{cases}$$

Step 2 : Equivalent Conditions

Fourier-Robin b.c.

Fourier-Robin b.c. : $\partial_n p_\epsilon - i\kappa p_\epsilon = 0$ on Γ^ϵ

- $k = 0$:

$$\mathbf{T}(\mathbf{u}_\epsilon^0) - i\omega c \rho_f \mathbf{u}_\epsilon^0 \cdot \mathbf{n} \mathbf{n} = \mathbf{g}_{0,\epsilon} \quad \text{on } \Gamma$$

- $k = 1$:

$$\mathbf{T}(\mathbf{u}_\epsilon^1) - i\omega c \rho_f \mathbf{u}_\epsilon^1 \cdot \mathbf{n} \mathbf{n} + \epsilon c^2 \rho_f (\Delta_\Gamma + \kappa^2 \mathbb{I} - 2i\kappa \mathcal{H} \mathbb{I})(\mathbf{u}_\epsilon^1 \cdot \mathbf{n}) \mathbf{n} = \mathbf{g}_{1,\epsilon} \quad \text{on } \Gamma$$

Step 3 : Stability and Convergence of Equivalent Conditions

Step 3.1 : Stability

Step 3.1 : Prove that problems $(\mathbf{P}_\varepsilon^k)$ are well-posed

Proposition

Under Assumption (SA), $\exists \varepsilon_0 > 0$ s.t. $\forall \varepsilon \in (0, \varepsilon_0)$, $\forall k \in \{0, 1, 2\}$, the problem $(\mathbf{P}_\varepsilon^k)$ with data $h_k \in L^2(\Gamma)$ has a unique solution $\mathbf{u}_\varepsilon^k \in H^1(\Omega_s)$

$$\|\mathbf{u}_\varepsilon^k\|_{1, \Omega_s} \leq C \|h_k\|_{0, \Gamma}$$

Application : Convergence of an asymptotic expansion of \mathbf{u}_ε^k as $\varepsilon \rightarrow 0$.

Step 3.2 : Convergence of Equivalent Conditions

Step 3.2 : Prove that the solution \mathbf{u}_ε^k satisfies an error estimate

$$\|\mathbf{u}_\varepsilon - \mathbf{u}_\varepsilon^k\|_{1,\Omega_s} \leq C\varepsilon^{k+1}.$$

Proof :

(i) Derive an expansion of \mathbf{u}_ε^k and show that :

$$\mathbf{u}_\varepsilon^k = \mathbf{u}_0 + \varepsilon\mathbf{u}_1 + \varepsilon^2\mathbf{u}_2 + \cdots + \varepsilon^k\mathbf{u}_k + \tilde{\mathbf{r}}_\varepsilon^{k+1}.$$

Recall :

$$\mathbf{u}_\varepsilon = \mathbf{u}_0 + \varepsilon\mathbf{u}_1 + \varepsilon^2\mathbf{u}_2 + \cdots + \varepsilon^k\mathbf{u}_k + \mathbf{r}_\varepsilon^{k+1}$$

hence,

$$\|\mathbf{u}_\varepsilon - \mathbf{u}_\varepsilon^k\|_{1,\Omega_s} = \|\mathbf{r}_\varepsilon^{k+1} - \tilde{\mathbf{r}}_\varepsilon^{k+1}\|_{1,\Omega_s}.$$

(ii) There holds

$$\mathbf{T}(\tilde{\mathbf{r}}_\varepsilon^{k+1}) + \mathbf{B}_{k,\varepsilon}(\tilde{\mathbf{r}}_\varepsilon^{k+1}) = \mathcal{O}(\varepsilon^{k+1}) \quad \text{on } \Gamma.$$

According to the step 3.1, we infer the uniform error estimates:

$$\|\tilde{\mathbf{r}}_\varepsilon^{k+1}\|_{1,\Omega_s} \leq C\varepsilon^{k+1}.$$

Outline

- 1 Uniform Estimates
- 2 Equivalent Conditions
- 3 Numerical Simulations**

Finite Element Method

Joint work with : J. Diaz (INRIA).

We use a Discontinuous Galerkin Method (IPDGM).

- 2D Computational domain : Ω_s is a disk of radius 0.01
- $\omega = 1.5 \times 10^6$
- Source : $p_i(\mathbf{x}) = \exp(i\omega \mathbf{x} \cdot \mathbf{d})$ with $\mathbf{d} = (1, 0)$
- \mathbb{P}_3 -finite elements (Lagrange) available in the Library [Hou10ni](#)
- Navier equation :

$$\mu \Delta \mathbf{u} + (\lambda + \mu) \nabla \operatorname{div} \mathbf{u} + \omega^2 \rho \mathbf{u} = 0 \quad \text{in } \Omega_s$$

with Lamé coefficients : $\mu = 26.32 \times 10^9$ and $\lambda = 51.08 \times 10^9$.

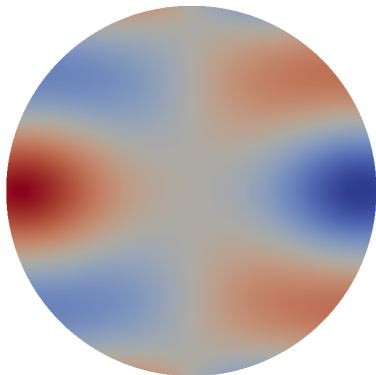
- $c = 1500 \text{ m.s}^{-1}$, $\rho_f = 1000 \text{ kg.m}^{-3}$, $\rho = 2700 \text{ kg.m}^{-3}$.

Numerical Simulations

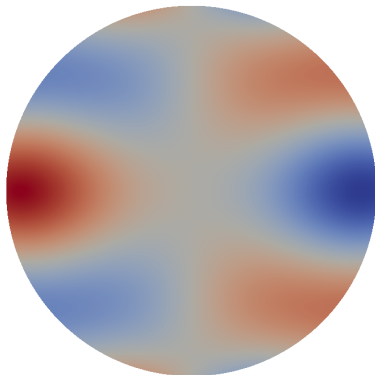
$\varepsilon = 0.0001$;

\mathbf{u}_ε : analytical solution;

\mathbf{u}_ε^2 : FE solution (equivalent model of order 2).



$|\operatorname{Re} \mathbf{u}_\varepsilon|$



$|\operatorname{Re} \mathbf{u}_\varepsilon^2|$

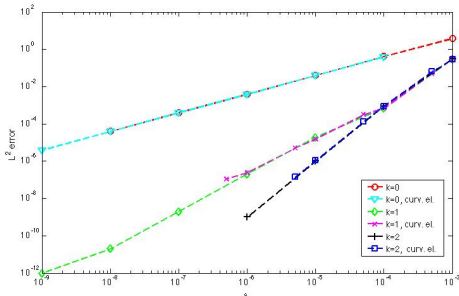
Convergence of the models

Dirichlet b.c.

For $k \in \{0, 1, 2\}$, we plot the L^2 -errors $\|\mathbf{u}_\varepsilon - \mathbf{u}_\varepsilon^k\|_{0, \Omega_s}$ w.r.t. ε :

\mathbf{u}_ε : analytical solution

\mathbf{u}_ε^k : analytical solution / FE solutions with Curved elements



The convergence rate coincide with the theory $\|\mathbf{u}_\varepsilon - \mathbf{u}_\varepsilon^k\|_{0, \Omega_s} = \mathcal{O}(\varepsilon^{k+1})$

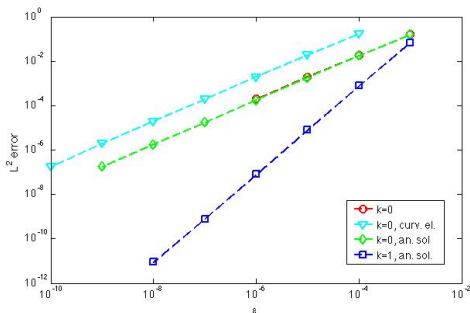
Convergence of the models

Fourier-Robin b.c.

For $k \in \{0, 1\}$, we plot the L^2 -errors $\|\mathbf{u}_\epsilon - \mathbf{u}_\epsilon^k\|_{0, \Omega_s}$ w.r.t. ϵ ,

\mathbf{u}_ϵ : analytical solution

\mathbf{u}_ϵ^k : analytical solution / FE solutions



Conclusion

- 1 Time dependent Equivalent Conditions
- 2 Higher Order Equivalent Conditions
- 3 Thin layer with variable thickness

Thank you for your attention!