



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

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

VICTOR PÉRON

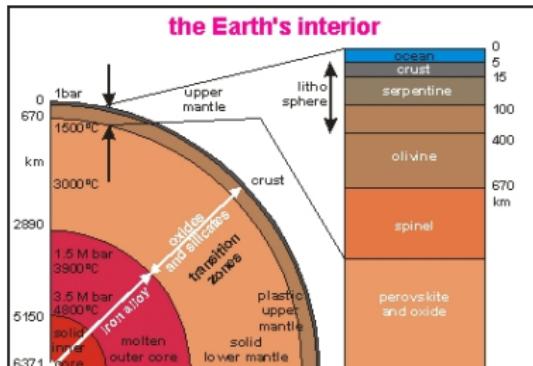
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Motivations

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

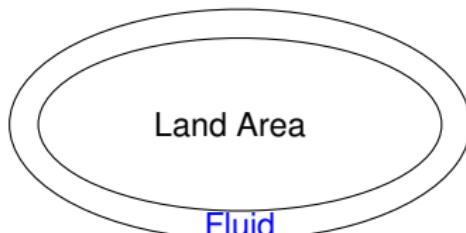


- The medium : a Land Area surrounded by a thin Fluid zone

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-LEMRABET 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 $\Omega^\varepsilon = \Omega_s \cup \Gamma \cup \Omega_f^\varepsilon$:

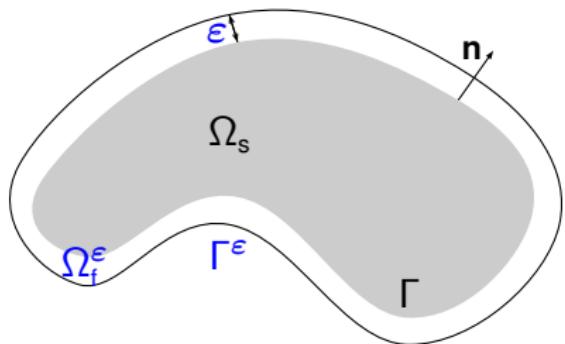
$$\Delta p + \kappa^2 p = 0 \quad \text{in } \Omega_f^\varepsilon$$

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

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

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

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



Assumption

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

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

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

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

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

$$\begin{aligned}
 a_\varepsilon((\mathbf{u}, p), (\mathbf{v}, q)) &:= \int_{\Omega_f^\varepsilon} (\nabla p \cdot \nabla \bar{q} - \kappa^2 p \bar{q}) \, d\mathbf{x} \\
 &+ \int_{\Omega_s} (\underline{\mathcal{C}}(x) \underline{\nabla} \mathbf{u} : \underline{\nabla} \bar{\mathbf{v}} - \omega^2 \rho \mathbf{u} \bar{\mathbf{v}}) \, d\mathbf{x} + \int_{\Gamma} (\omega^2 \rho_f \mathbf{u} \cdot \mathbf{n} \bar{q} + p \bar{\mathbf{v}} \cdot \mathbf{n}) \, ds
 \end{aligned}$$

Uniform Estimates

Some resonant frequencies may appear in the solid

Assumption (SA)

The angular frequency ω is not an eigenfrequency of the problem

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

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 $(\mathbf{u}_\varepsilon, p_\varepsilon) \in V_\varepsilon$ and

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

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

Key for the proof: introduce a "Scaled Problem"

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

Formulation in a fixed domain

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

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

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

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

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 $(\mathfrak{P})_{\varepsilon_m}$ associated with $\varepsilon_m \rightarrow 0$ and $\mathfrak{F}_m \in V'$ such that

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

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

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

and that \mathbf{u}_1 solves

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

Step 1 : Multiscale Expansion

First terms

- At step $n = 2$,

$$\mathfrak{p}_2(., Y_3) = (S^2 - 1) \mathcal{H}[\rho_f \omega^2 \mathbf{u}_0 \cdot \mathbf{n} - \partial_{\mathbf{n}} p_i] + (S - 1) \rho_f \omega^2 \mathbf{u}_1 \cdot \mathbf{n}$$

and then, \mathbf{u}_2 solves

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

Step 1 : Validation of the Asymptotic Expansion

Aim : proving Estimates for Remainders

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

Evaluation of the right hand sides in

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

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

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

Step 2 : Equivalent Conditions on Γ

Identify a simpler problem

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

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.

- $k = 0$:

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

- $k = 1$:

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

- $k = 2$:

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

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

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

We infer a simpler problem

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

Step 2 : Equivalent Conditions

Fourier-Robin b.c.

Fourier-Robin b.c. : $\partial_{\mathbf{n}} \mathbf{p}_{\varepsilon} - i\kappa \mathbf{p}_{\varepsilon} = 0$ on Γ^{ε}

- $k = 0$:

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

- $k = 1$:

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

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 $u_\varepsilon^k \in H^1(\Omega_s)$

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

Application : Convergence of an asymptotic expansion of 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 $\lambda = 51.08 \times 10^9$.

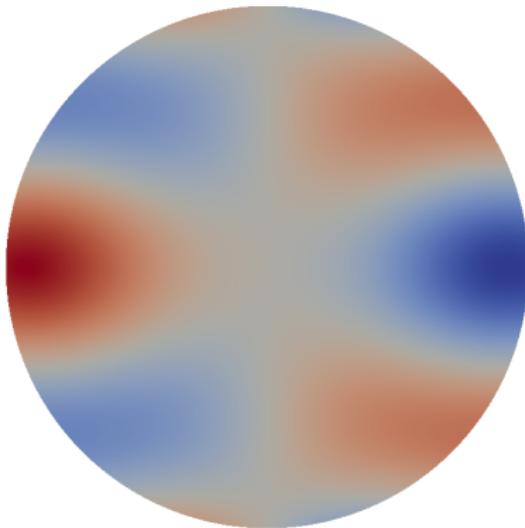
- $c = 1500 \text{ m.s}^{-1}$, $\rho_f = 1000 \text{ kg.m}^{-3}$, $\rho = 2700 \text{ kg.m}^{-3}$.

Numerical Simulations

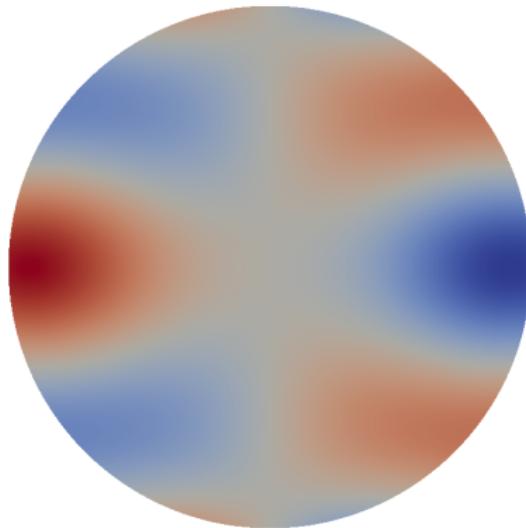
$\varepsilon = 0.0001$;

\mathbf{u}_ε : analytical solution;

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



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



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

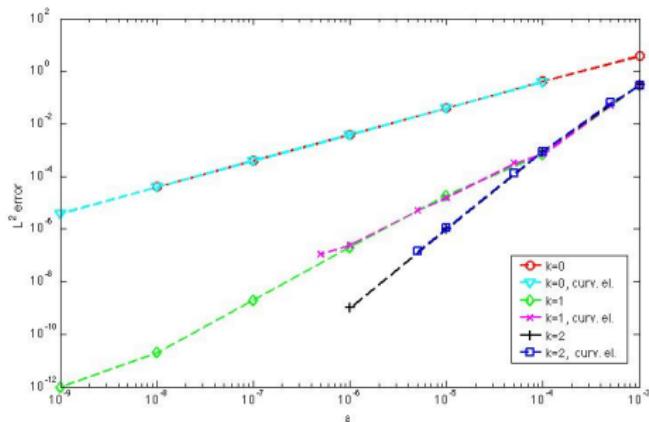
Convergence of the models

Dirichlet b.c.

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

u_ε : analytical solution

u_ε^k : analytical solution / FE solutions with Curved elements



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

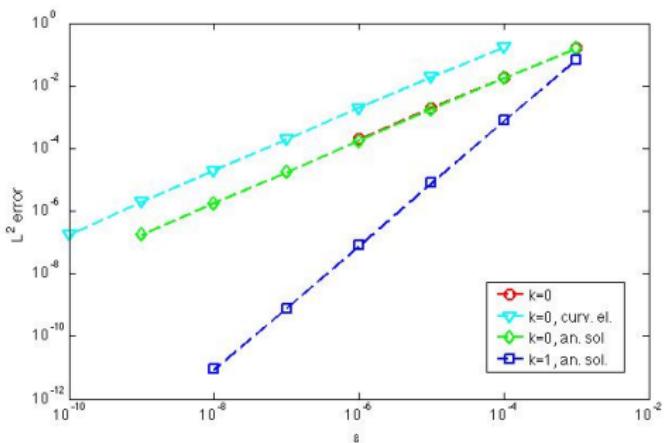
Convergence of the models

Fourier-Robin b.c.

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

\mathbf{u}_ε : analytical solution

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



Conclusion

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

Thank you for your attention!