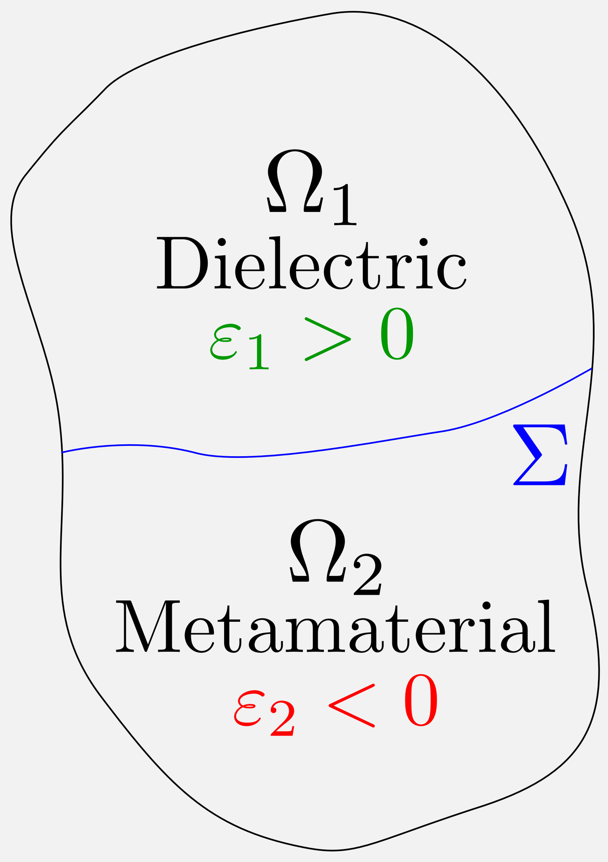
Radiation condition for a non-smooth interface between a dielectric and a metamaterial

L. Chesnel with A.S. Bonnet-Ben Dhia, P. Ciarlet Jr. and X. Claeys
POEMS, UMR 7231 CNRS-ENSTA-INRIA, École Polytechnique, Paris

Studied problem

▶ Time harmonic problem in a heterogeneous medium Ω.
Difficulty concentrated in the electrostatic case.



▶ Define the space of finite energy fields:

$$H^1_0(\Omega) = \{v \in L^2(\Omega) \,|\, \int_\Omega |\nabla v|^2 \, d\Omega < \infty;\ v|_{\partial\Omega} = 0\}.$$

$(\mathcal{P})$ Find $u \in H^1_0(\Omega)$ such that: $-\mathrm{div}(\varepsilon\, \nabla u) = f$ in Ω.

▶ $(\mathcal{P})$ is equivalent to the variational problem:

$(\mathcal{P}_V)$ Find $u \in H^1_0(\Omega)$ such that: $\displaystyle\int_\Omega \varepsilon\, \nabla u \cdot \nabla v \, d\Omega = \int_\Omega f v \, d\Omega\ ,\forall v \in H^1_0(\Omega).$

Difficulties :

- Loss of coercivity: there is no constant C such that
$$\int_\Omega \varepsilon\, |\nabla u|^2 \, d\Omega > C \int_\Omega |\nabla u|^2 \, d\Omega,\ \forall u \in H^1_0(\Omega).$$
- Add some dissipation (modeled by η) is not sufficient:
$$|\int_\Omega \varepsilon^\eta\, |\nabla u^\eta|^2 \, d\Omega\,| > \frac{C}{\eta} \int_\Omega |\nabla u^\eta|^2 \, d\Omega.$$

Questions :

▷ Is problem $(\mathcal{P})$ well-posed ?
▷ How to compute a numerical approximation of the solution ?
▷ New model when $(\mathcal{P})$ is ill-posed?

The T-coercivity approach

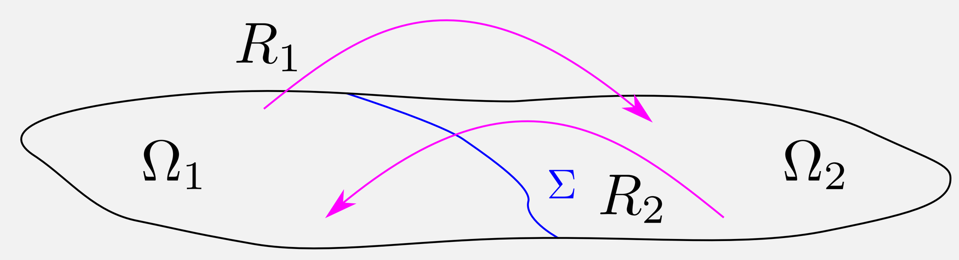
① Consider $\mathtt{T}_1\, u = \begin{vmatrix} u_1 & \text{in } \Omega_1 \\ -u_2 + 2R_1\, u_1 & \text{in } \Omega_2 \end{vmatrix}$, where R_1 is such that $\mathtt{T}_1\, u \in H^1_0(\Omega)$.

② $\displaystyle\int_\Omega \varepsilon\, \nabla u \cdot \nabla(\mathtt{T}_1\, u)\, d\Omega \geq C \int_\Omega |\nabla u|^2 \, d\Omega$ for $\varepsilon_1 \geq \|R_1\|^2\, |\varepsilon_2|$.

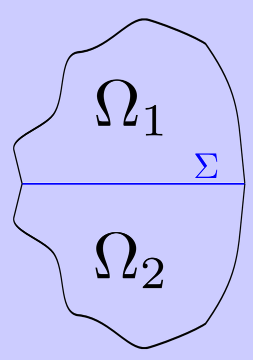
③ Since $\mathtt{T}_1$ is an isomorphism of $H^1_0(\Omega)$ (notice that $\mathtt{T}_1^{-1} = \mathtt{T}_1$), $(\mathcal{P}_V)$, and so $(\mathcal{P})$, is well-posed when $\varepsilon_1 \geq \|R_1\|^2\, |\varepsilon_2|$.

④ One proceeds in the same way with $\mathtt{T}_2$ built from $R_2 : \Omega_2 \to \Omega_1$.

THEOREM. If the contrast $\kappa_\varepsilon = \varepsilon_2/\varepsilon_1 \notin I_\Sigma = [-\|R_2\|^2; -1/\|R_1\|^2]$ (critical interval) then problem $(\mathcal{P})$ is well-posed.

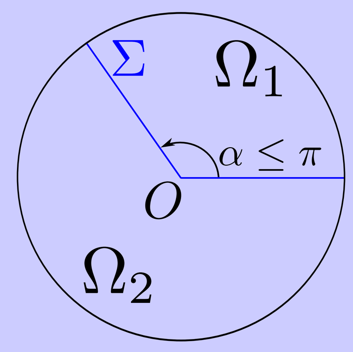


▶ This technique can be used to justify the classical finite element methods and to study the Maxwell's problem (A.S. Bonnet-Ben Dhia's talk).



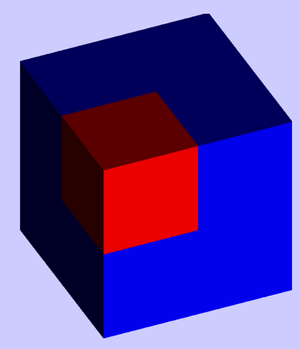
SYMMETRICAL DOMAIN

$R_1 = S_\Sigma$ and $R_2 = S_\Sigma$ (symmetry).
$I_\Sigma = \{-1\}$.



2D CORNER

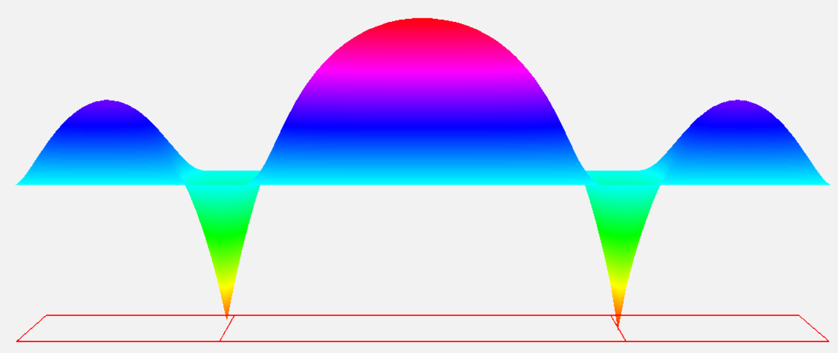
R_1 and R_2 obtained from symmetry/dilatation w.r.t. θ.
$I_\Sigma = [-\frac{2\pi-\alpha}{\alpha}; -\frac{\alpha}{2\pi-\alpha}]$.

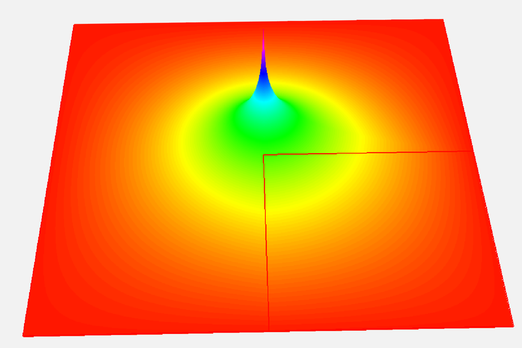


FICHERA'S CORNER

R_1 and R_2 obtained from the symmetries S_{Ox}, S_{Oy}, S_{Oz}.
$I_\Sigma = [-7; -1/7]$.

▶ If Σ is smooth, $(\mathcal{P})$ is well-posed for $\kappa_\varepsilon \neq -1$.
▶ If Σ has a corner, $(\mathcal{P})$ is well-posed for $\kappa_\varepsilon \notin I_\Sigma$ (open interval).
But one observes a field of strong intensity in a neighbourhood of the corner.
⇒ What happens in the critical interval I_Σ?



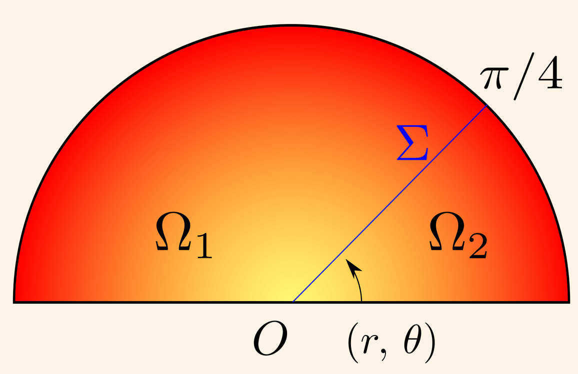


A black hole phenomena

Singularity problem

Helmholtz equation in the bounded sector Ω

$$-\mathrm{div}(\varepsilon\, \nabla u) = -r^{-2}(\varepsilon(r\partial_r)^2 + \partial_\theta \varepsilon \partial_\theta)u = f.$$

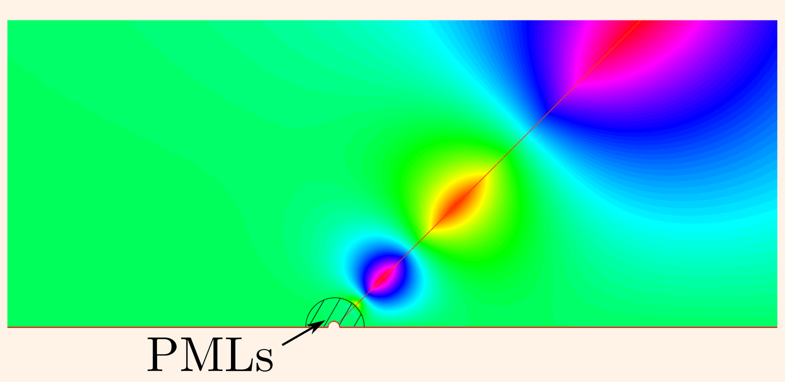


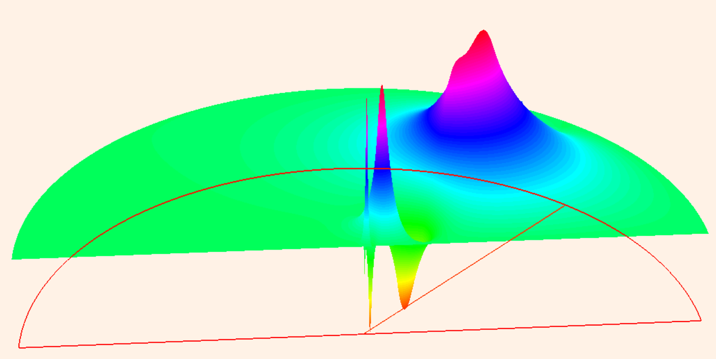
▶ For $\kappa_\varepsilon \in (-1; -1/3)$, propagative singularities appear:

$s_1^\mp(r,\theta) = \varphi_1(\theta) e^{\mp i\eta \ln r}$ where η is a real number which depends on κ_ε.

▶ Radiation condition in O to select the good singularity.

▶ Use of PMLs in O to approach the solution which is not of finite energy.





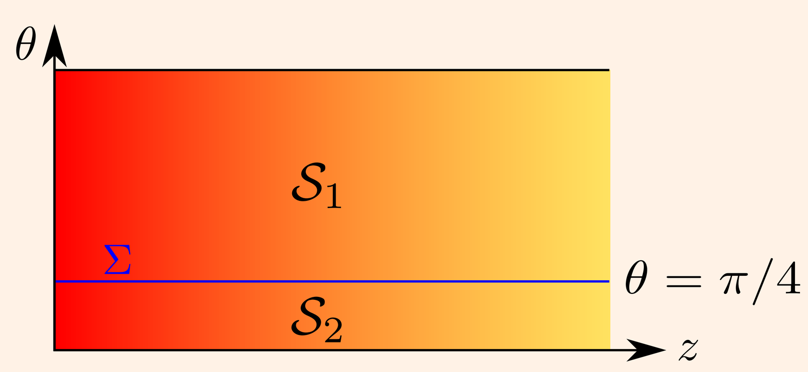
$$(z,\theta) = (-\ln r, \theta)$$

$$(r,\theta) = (e^{-z}, \theta)$$

Waveguide problem

Helmholtz equation in the strip $\mathcal{S}$

$$-\mathrm{div}(\varepsilon\, \nabla u) = -(\varepsilon \partial_z^2 + \partial_\theta \varepsilon \partial_\theta)u = e^{-2z} f.$$



▶ For $\kappa_\varepsilon \in (-1; -1/3)$, propagative modes appear:

$m_1^\pm(z,\theta) = \varphi_1(\theta) e^{\pm i\eta z}$ where η is a real number which depends on κ_ε.

▶ Radiation condition in $+\infty$ to select the outgoing mode.

▶ Use of PMLs in $+\infty$ to truncate the domain and to use classical finite element methods.