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SEM-DG Approximation for elasto-acoustics

Hélène Barucq¹, Henri Calandra², Aurélien Citrain^{3,1}, Julien Diaz¹ and Christian Gout³

¹ Team project Magique.3D, INRIA, E2S UPPA, CNRS, Pau, France.

² TOTAL SA, CSTJF, Pau, France.

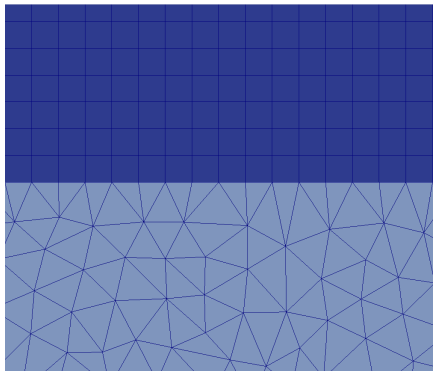
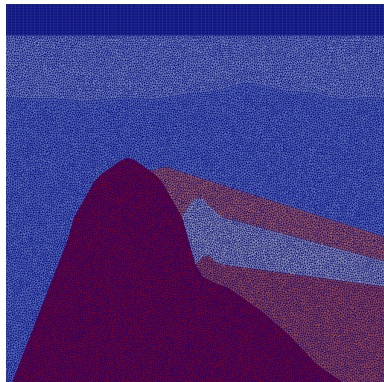
³ INSA Rouen-Normandie Université, LMI EA 3226, 76000, Rouen.

MATHIAS 2018 October 22-24



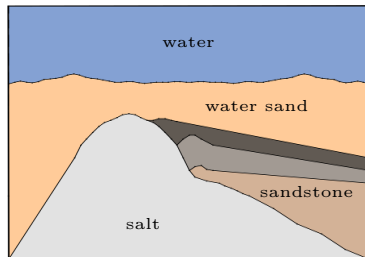
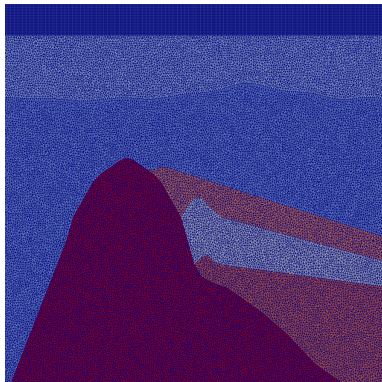
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Why using hybrid meshes?



- Useful when the use of unstructured grid is non-sense (e.g. medium with a layer of water).
- Well suited for the coupling of numerical methods in order to reduce the computational cost and improve the accuracy.

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$x \in \Omega \subset \mathbb{R}^d$, $t \in [0, T]$, $T > 0$:

$$\begin{cases} \rho(x) \frac{\partial v}{\partial t}(x, t) &= \nabla \cdot \underline{\underline{\sigma}}(x, t), \\ \frac{\partial \underline{\underline{\sigma}}}{\partial t}(x, t) &= \underline{\underline{C}}(x) \underline{\underline{\epsilon}}(v(x, t)). \end{cases}$$

With:

- $\rho(x)$ the density,
- $\underline{\underline{C}}(x)$ the elasticity tensor,
- $\underline{\underline{\epsilon}}(x, t)$ the deformation tensor,
- $v(x, t)$, the wavespeed,
- $\underline{\underline{\sigma}}(x, t)$ the strain tensor.

Software written in **Fortran** for wave propagation simulation in the **time domain**

Features

Simulation:

- on various types of meshes (**unstructured triangles and tetrahedra**),
 - on **heterogeneous media (acoustic, elastic and elasto-acoustic)**.
-
- **Discontinuous Galerkin (DG)** based on **unstructured triangles and unstructured tetrahedra**,
 - with various time-schemes : **Runge-Kutta (2 or 4), Leap-Frog**,
 - with **multi-order** computation(**p-adaptivity**)...

- 1 Numerical Methods
- 2 Comparison DG/SEM on structured quadrangle mesh
- 3 DG/SEM coupling
- 4 3D extension

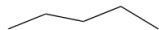
1 Numerical Methods

- Discontinuous Galerkin Method (DG)
- Spectral Element Method (SEM)
- Advantages of each method

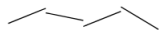
Use discontinuous functions :



mesh

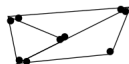


continuous

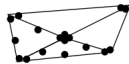


discontinuous

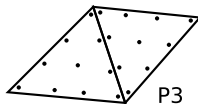
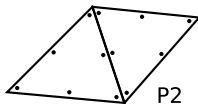
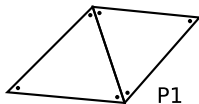
h adaptivity :



p adaptivity :

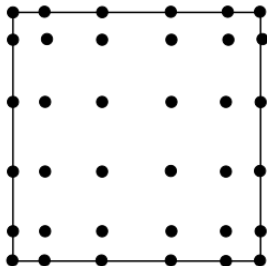


Degrees of freedom necessary on each cell :



General principle

- Finite Element Method (FEM) discretization + Gauss-Lobatto quadrature,
- Gauss-Lobatto points as degrees of freedom (gives us exponential convergence on L^2 -norm).



- $\int f(x) dx \approx \sum_{j=1}^{N+1} \omega_j f(\xi_j),$
- $\varphi_i(\xi_j) = \delta_{ij}.$

DG

- Element per element computation (*hp*-adaptivity).
- Time discretization quasi explicit (block diagonal mass matrix).
- Simple to parallelize.
- Robust to brutal changes of physics and geometry

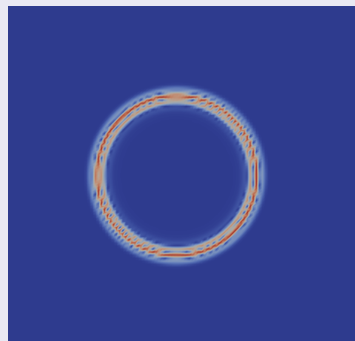
SEM

- Couples the flexibility of FEM with the accuracy of the pseudo-spectral method.
- Simplifies the mass and stiffness matrices (mass matrix diagonal).

2 Comparison DG/SEM on structured quadrangle mesh

- Description of the test cases
- Comparative tables

Physical parameters



| | |
|---------------|-------------------------|
| P wavespeed | 1000 m.s^{-1} |
| Density | 1 kg.m^{-3} |

Second order **Ricker Source** in P wave
($f_{peak} = 10\text{Hz}$)

General context

- **Acoustic homogeneous** medium.
- Four different meshes : **10000 cells**, **22500 cells**, **90000 cells**, **250000 cells**.
- CFL computed using **power iteration** method.
- **Leap-Frog** time scheme.
- **Eight threads** parallel execution with **OpenMP**.

- Error computed as the difference between an analytical and a numerical solution for each method.
- Three cases considered : DG without penalization terms, DG with penalization terms and SEM.

| | CFL | L2-error | CPU-time | Nb of time steps |
|--------------------|---------|----------|----------|------------------|
| DG($\alpha = 0$) | 3.18e-3 | 2e-1 | 5.13 | 629 |
| SEM | 4.9e-3 | 5e-2 | 0.80 | 409 |

Figure: DG not penalized and SEM comparison on the 10000 cells case

| | CFL | L2-error | CPU-time(s) | Nb of time steps |
|--------------------|---------|----------|-------------|------------------|
| DG($\alpha = 0$) | 2.12e-3 | 7e-1 | 18.11 | 943 |
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Figure: DG not penalized and SEM comparison on the 20000 cells case

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Figure: DG penalized and SEM comparison using the same CFL on a 10000 thousands cells mesh

| | CFL | L2-error | CPU-time(s) | Nb of time steps |
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| DG ($\alpha = 0.5$) | 1.33e-3 | 2e-2 | 32.98 | 1502 |
| SEM | 1.33e-3 | 2e-2 | 8.67 | 1502 |

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- Element per element computation (*hp*-adaptivity).
- Time discretization quasi explicit (block diagonal mass matrix).
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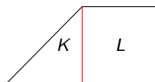
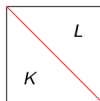
SEM

- Couples the flexibility of FEM with the accuracy of the pseudo-spectral method.
- Simplifies the mass and stiffness matrices (mass matrix diagonal).
- **Reduces the computational costs on structured quadrangle cells in comparison with DG**

- 3 DG/SEM coupling
 - Hybrid meshes structures
 - Variational formulation

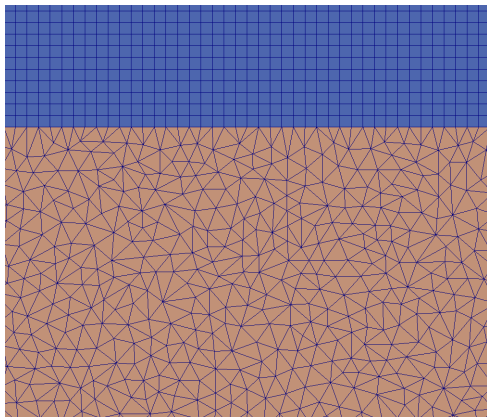
- Aim at coupling P_k and Q_k structures.
- Need to extend or split some structures (e.g. neighbour indexes).
- Define new face matrices:

$$M_{ij}^{K,L} = \int_{K \cap L} \phi_i^K \phi_j^L, \quad M_{ij}^{K,L} = \int_{K \cap L} \psi_i^K \psi_j^L, \quad M_{ij}^{K,L} = \int_{K \cap L} \phi_i^K \psi_j^L.$$



Global context

- Domain in two parts : $\Omega_{h,1}$ (**structured quadrangles + SEM**), $\Omega_{h,2}$ (**unstructured triangles + DG**).



SEM variational formulation :

$$\begin{cases} \int_{\Omega_{h,1}} \rho \partial_t v_1 \cdot w_1 = - \int_{\Omega_{h,1}} \sigma_1 \cdot \nabla w_1 + \int_{\Gamma_{out,1}} (\sigma_1 \mathbf{n}_1) \cdot w_1, \\ \int_{\Omega_{h,1}} \partial_t \sigma_1 : \xi_1 = - \int_{\Omega_{h,1}} (\nabla(C\xi_1)) \cdot v_1 + \int_{\Gamma_{out,1}} (C\xi_1 \mathbf{n}_1) \cdot v_1. \end{cases}$$

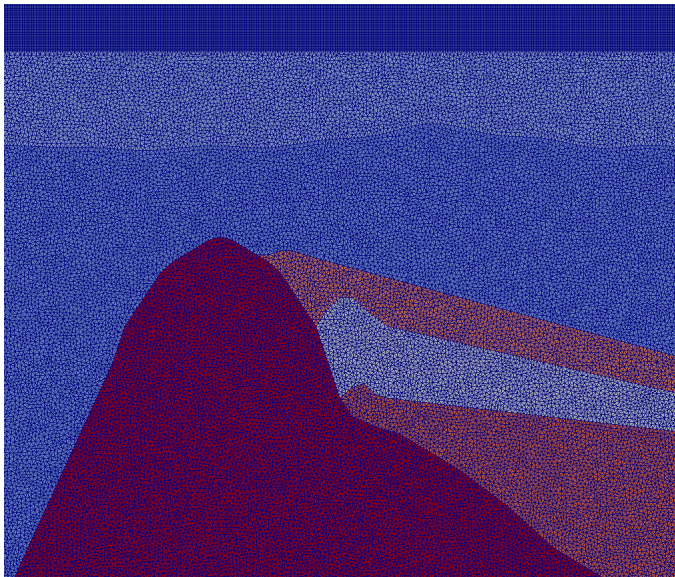
DG variational formulation :

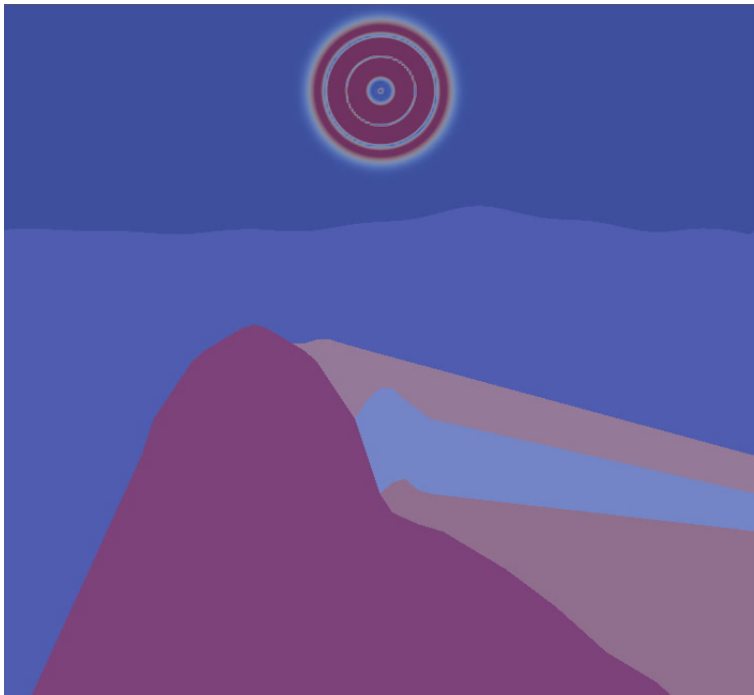
$$\begin{cases} \int_{\Omega_{h,2}} \rho \partial_t v_2 \cdot w_2 = - \int_{\Omega_{h,2}} \sigma_2 \cdot \nabla w_2 + \int_{\Gamma_{out,2}} (\sigma_2 \mathbf{n}_2) \cdot w_2 + \int_{\Gamma_{int}} \{ \{ \sigma_2 \} \} [[w_2]] \cdot \mathbf{n}_2, \\ \int_{\Omega_{h,2}} \partial_t \sigma_2 : \xi_2 = - \int_{\Omega_{h,2}} (\nabla(C\xi_2)) \cdot v_2 + \int_{\Gamma_{out,2}} (C\xi_2 \mathbf{n}_2) \cdot v_2 + \int_{\Gamma_{int}} \{ \{ v_2 \} \} [[C\xi_2]] \cdot \mathbf{n}_2. \end{cases}$$

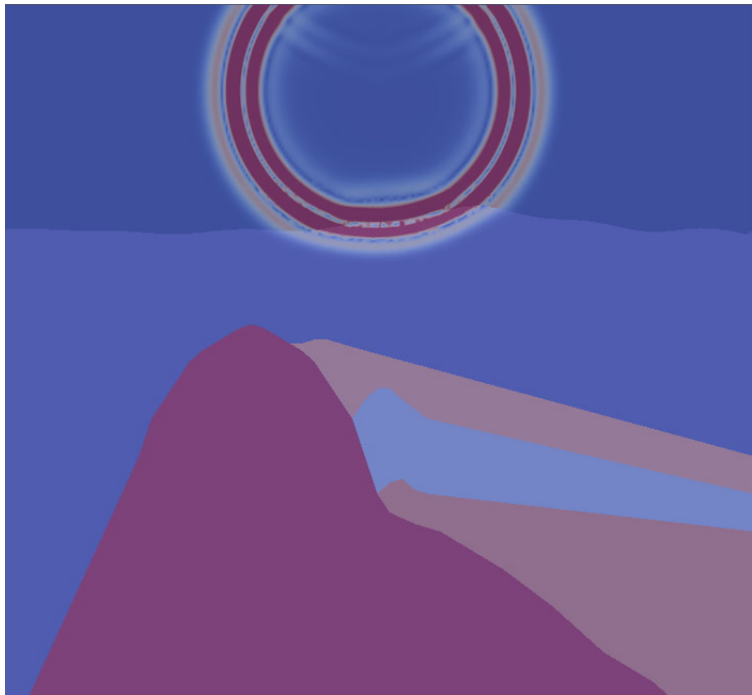
$$\left\{ \begin{aligned}
 & \int_{\Omega_{h,1}} \rho \partial_t v_1 \cdot w_1 + \int_{\Omega_{h,2}} \rho \partial_t v_2 \cdot w_2 = - \int_{\Omega_{h,1}} \sigma_1 \cdot \nabla w_1 - \int_{\Omega_{h,2}} \sigma_2 \cdot \nabla w_2 \\
 & + \int_{\Gamma_{out,1}} (\sigma_1 \mathbf{n}_1) \cdot w_1 + \int_{\Gamma_{out,2}} (\sigma_2 \mathbf{n}_2) \cdot w_2 + \int_{\Gamma_{int}} \{ \{ \sigma_2 \} \} [[w_2]] \cdot \mathbf{n}_2 \\
 & + \int_{\Gamma_{1/2}} [[\sigma w]] \cdot \mathbf{n}, \\
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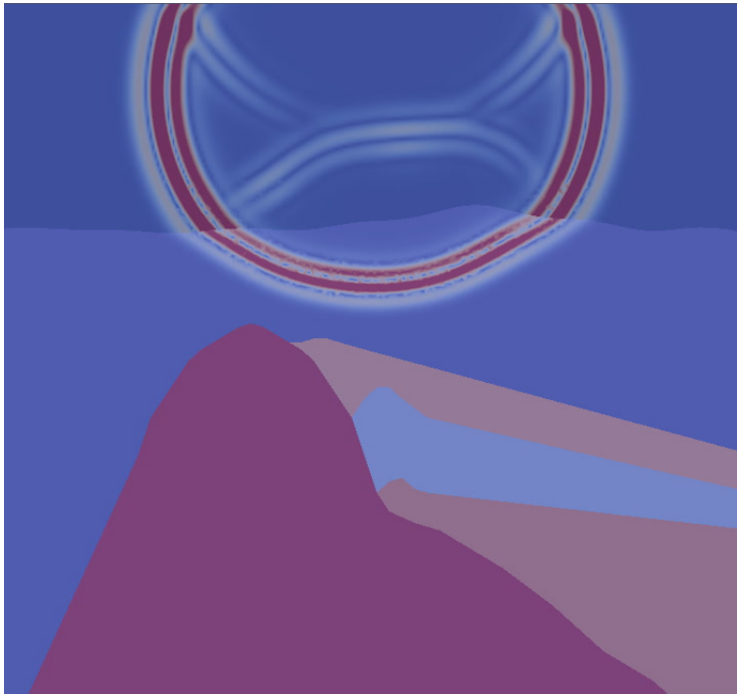
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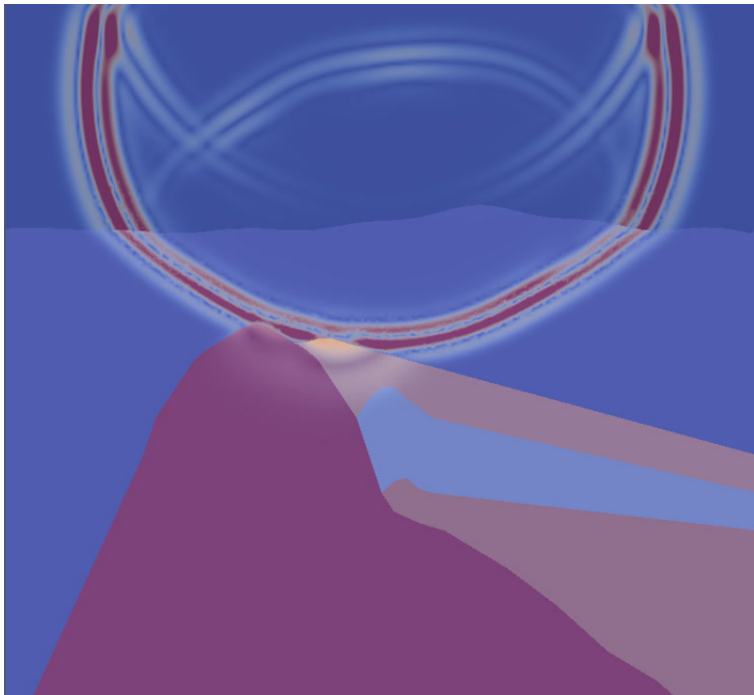
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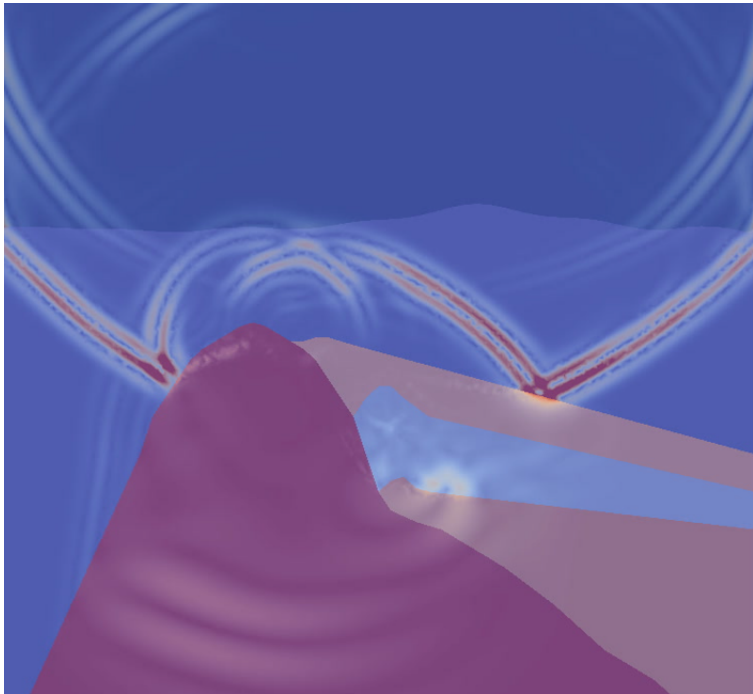












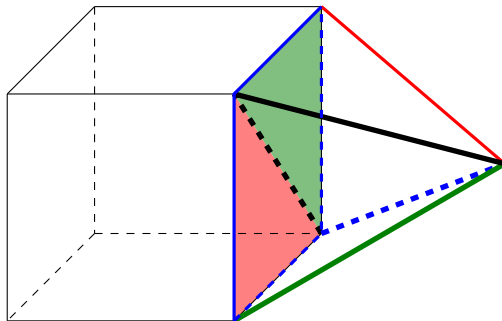


Figure: Hexa/Tet boundary configuration

- Only deal with a simple case of 3D hybrid meshes : one hexahedron has only two tetrahedra as neighbour.
- Extend SEM in 3D (basis functions...).
- Require introducing a new matrix which handles the rotation cases between two elements.

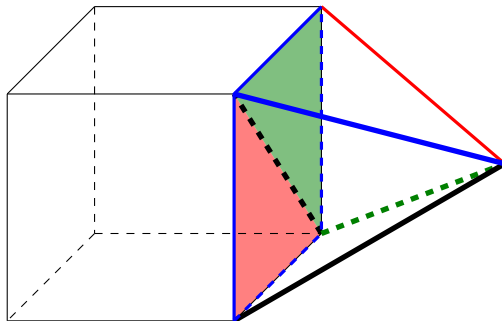


Figure: Hexa/Tet boundary configuration

- Only deal with a simple case of 3D hybrid meshes : one hexahedron has only two tetrahedra as neighbour.
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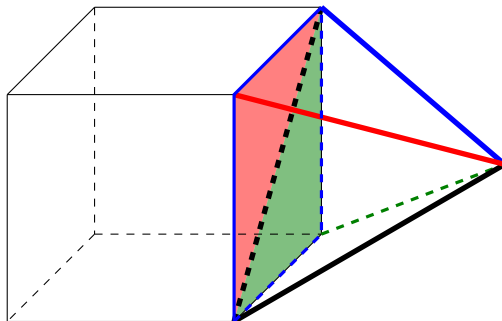


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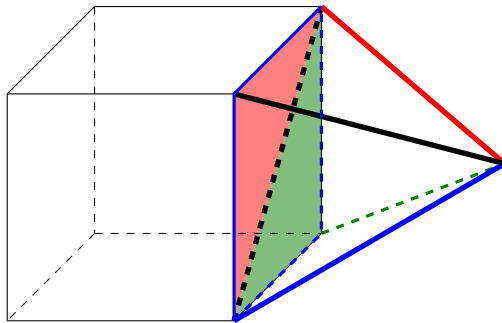
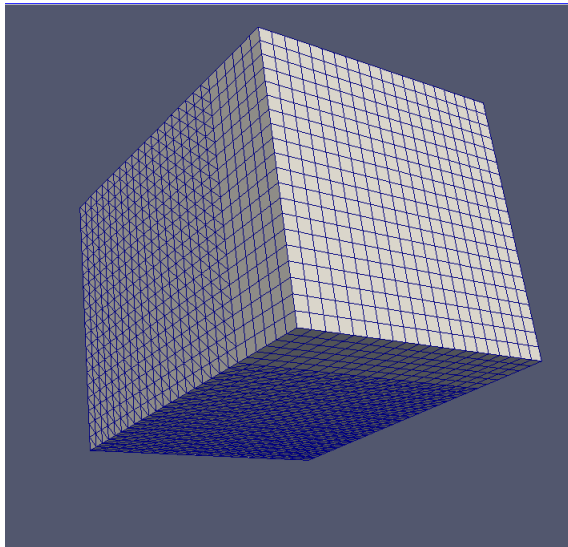
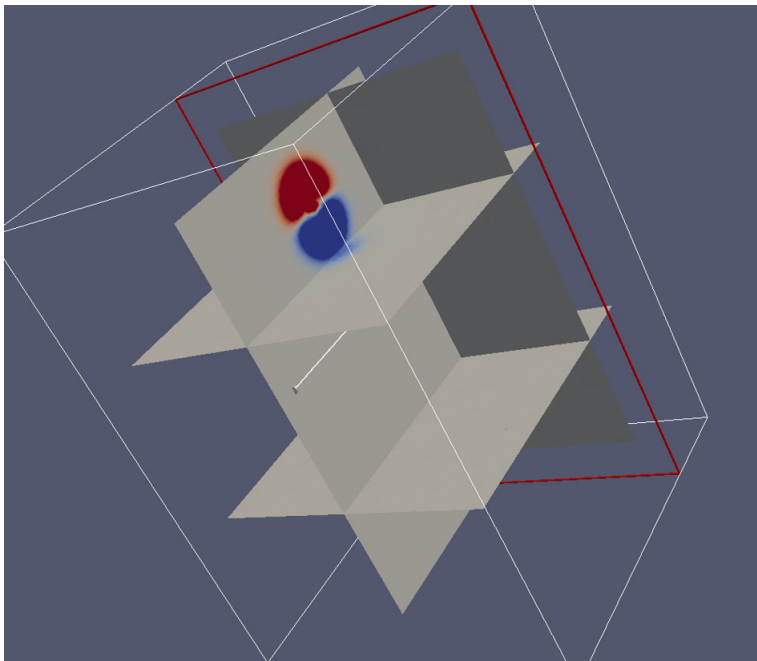
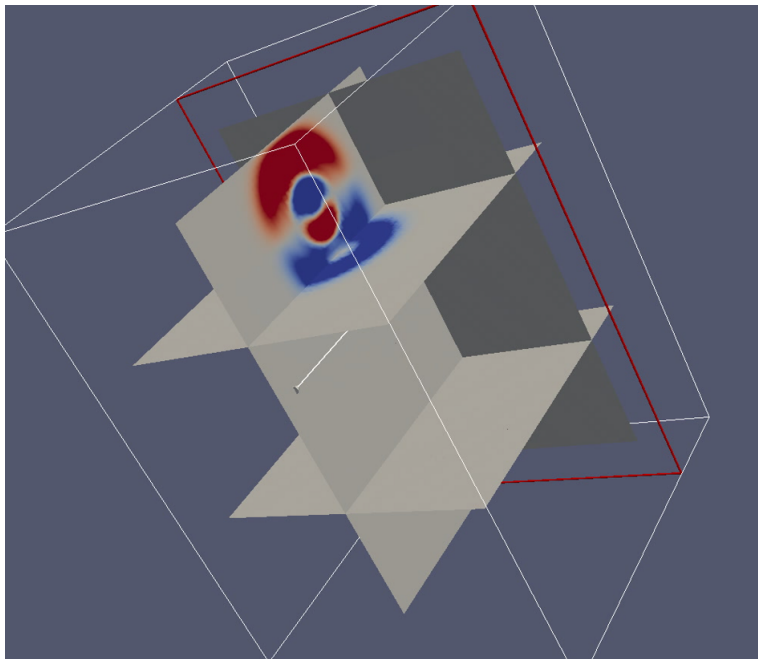


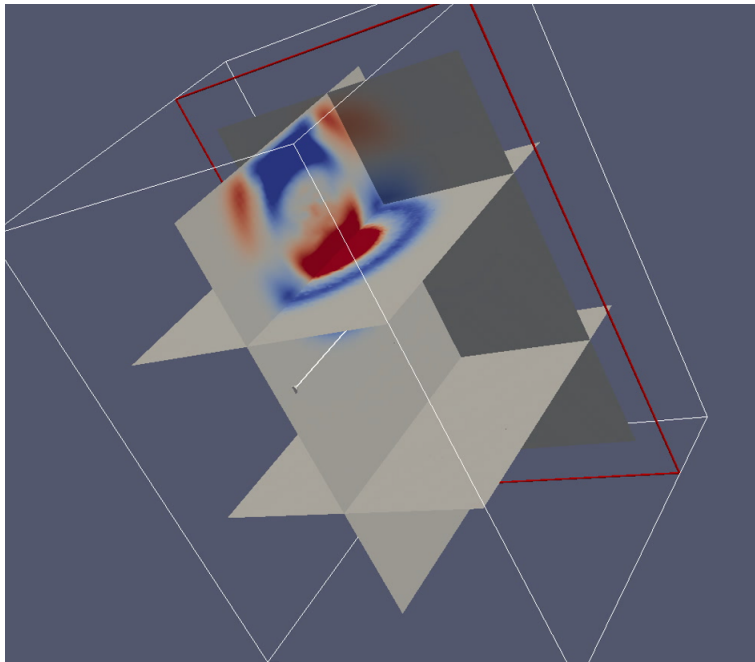
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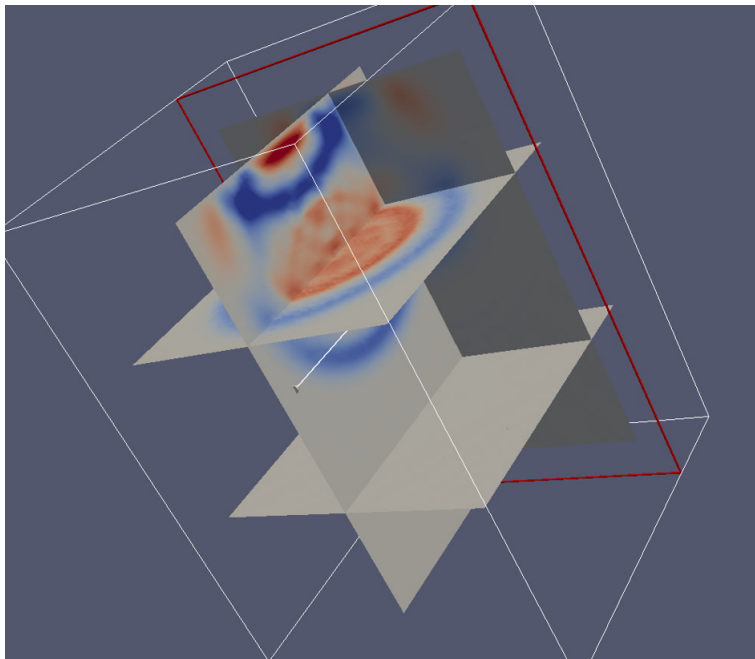
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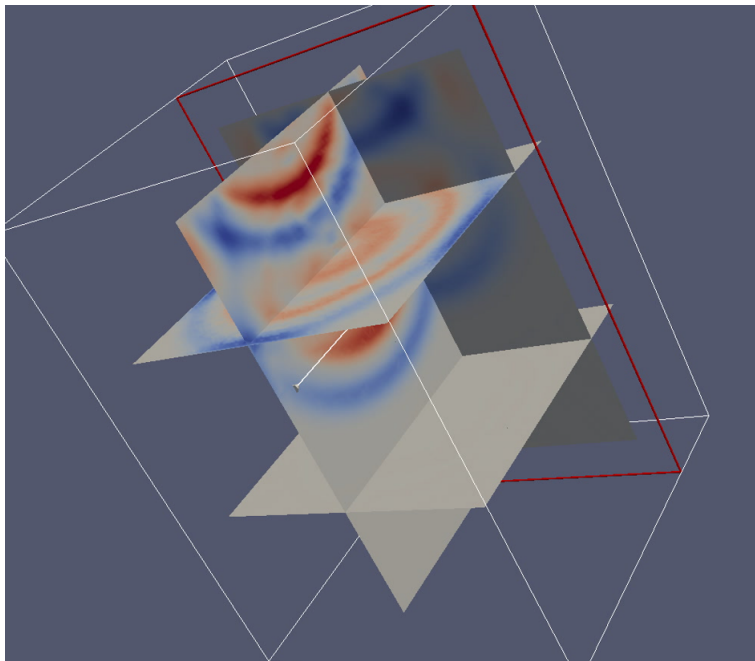


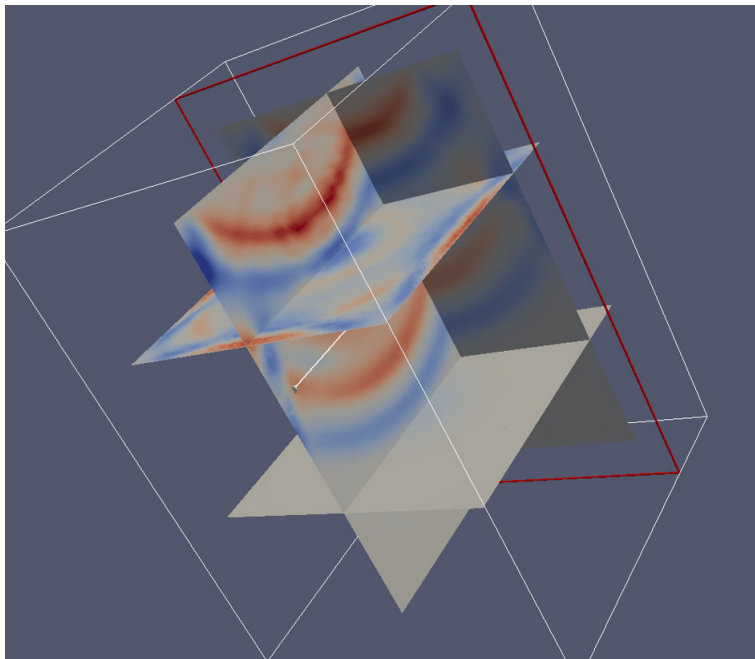


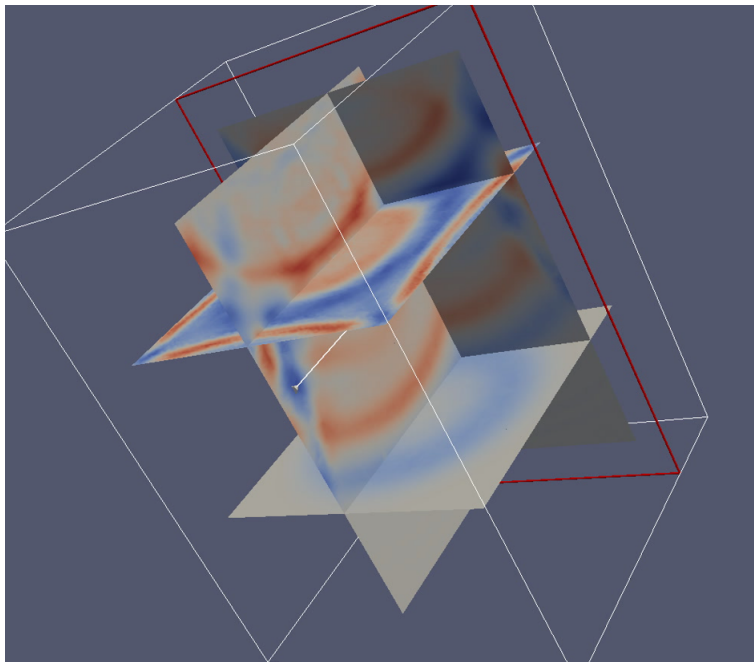












Conclusion

- 1 SEM is more efficient on structured quadrangle mesh than DG
- 2 Build a variational formulation for DG/SEM coupling and find a CFL condition that ensures stability
- 3 Show the utility of using hybrid meshes and method coupling (reduce computational cost,...)

Perspectives

- Implement DG/SEM coupling on the code (2D) ✓
- Develop DG/SEM coupling in 3D ✓
- Develop PML in the hexahedral part
- Add a local time-stepping scheme

Thank you for your attention !

Questions?

Error-order graphic

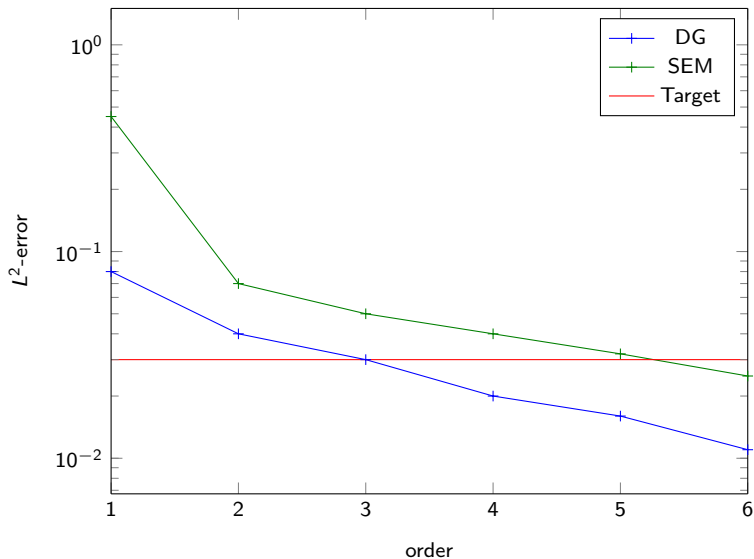


Figure: L^2 -error comparison on a 10000 cells mesh

Error-order graphic

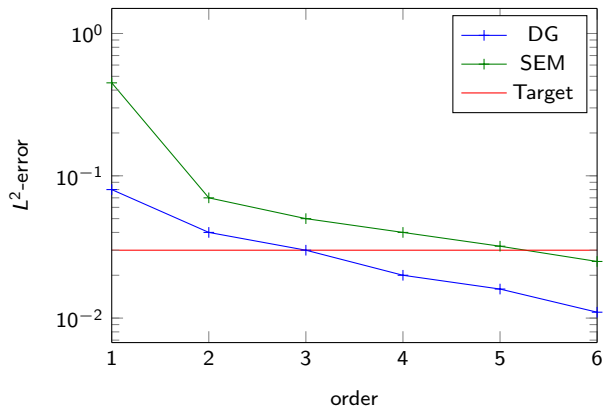


Figure: L^2 -error comparison on a 10000 cells mesh

| | CFL | L2-error | CPU-time | Nb of time steps |
|-----------------|---------|----------|----------|------------------|
| DG | 2e-3 | 3e-2 | 7.93 | 1000 |
| SEM(order five) | 2.13e-3 | 3e-2 | 9.06 | 943 |

Figure: SEM and DG comparison with fixed error