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On the development of locally implicit schemes for linear wave problems

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- Research code maintained by Marc Duruflé at INRIA (open-source).
- Frequency-domain and time domain modeling for wave propagation.

Main goals

- Several wave-field propagators
 - Acoustic, electromagnetic, aeroacoustic and elastodynamic.
- Different discretization methods
 - Spatial : FEM, DG, HDG
 - Time schemes: explicit and implicit one step, explicit multi-step.
- Uses several libraries like: Blas, Mumps, Lapack, SuperLU, GSL, ...

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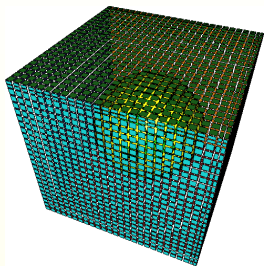
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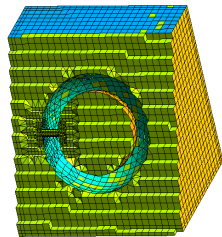
We have developed:

- ✓ Unconditionally stable implicit schemes (see [Barucq et al., 2017])
- ✓ Optimized CFL number explicit schemes (see the thesis [N'diaye, 2017]).
- ✓ Locally implicit schemes (see the thesis [N'diaye, 2017]).

Implicit and/or explicit high order time schemes?



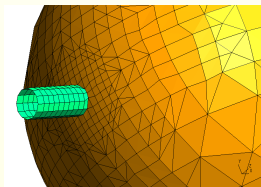
(a) Spherical resonant cavity



(b) Cross-section

24 885 elements

- 3 423 tetrahedra
- 16 571 hexahedra
- 4 246 pyramids
- 645 wedges



(c) Entry of the cavity

Implicit and/or explicit high order time schemes?

We consider the following ODE (Ordinary Differential equation):

$$M_h \frac{dy}{dt} + K_h y = f(t)$$

where M_h is the mass matrix and K_h is the stiffness matrix, obtained after space discretization on Ω .

The ODE is stiff because

- the eigenvalues of $M_h^{-1} K_h$ can be large,
- due to the presence of **small elements** in the computational mesh,
- or **high-order** space discretization.

Consequence

- ✓ Explicit methods become too expensive.
- ✓ Implicit methods are needed.
- ✓ But, implicit methods are highly memory consuming.

Implicit and/or explicit high order time schemes?

Table: Computational resources needed for explicit and implicit schemes for the scattering of the spherical resonant to obtained a relative L^2 error is below $1e-03$ (3D case HDG Acoustic). The direct solver MUMPS is used for implicit schemes. The computational times correspond to the maximal time when using 6 nodes Miriel and 144 cores on the PlaFRIM platform.

Q_4	24 885 elements		1 633 475 degrees of freedom	
Schemes	Memory (GiB)	Factorization (GiB)	Number of time-steps	Computational times
L-ERK4 – 2	1.1	-	24 000	1h08mn25s
L-ERK8 – 2	1.40	-	15 000	1h16mn16s
L-SDIRK3 – 1	35.04	29.38	3 000	1h19mn30s
L-SDIRK7 – 2	35.41	29.38	900	44mn03s
Pade4	68.86	58.67	3 000	40mn31s
Pade8	136.40	117.34	750	20mn08s

Implicit and/or explicit high order time schemes?

How about mixing explicit and implicit schemes ?

Outline

- 1 Methodology for the construction of a locally implicit method
- 2 Numerical convergence

- 1 Methodology for the construction of a locally implicit method
 - General idea to construct a locally implicit method
 - Treatment of the coarse region
 - Treatment of the fine region
 - Splitting of the Mesh into fine and coarse region

General idea to construct a locally implicit method

We consider

$$\frac{dy(t)}{dt} = Ay(t) + F(t), \quad (1)$$

with $A = -M_h^{-1}K_h$ and $F(t) = M_h^{-1}f(t)$.

We consider the following splitting

$$y(t) = y^{(c)}(t) + y^{(f)}(t)$$

where

$$\begin{aligned} y^{(c)} &= (I - P)y(t), \\ y^{(f)} &= Py(t). \end{aligned}$$

P is a diagonal matrix with

$$\begin{cases} P_{i,i} = 1, & \text{if } i \text{ is a degree of freedom in the refined mesh} \\ P_{i,i} = 0, & \text{if } i \text{ is a degree of freedom in the coarse mesh} \end{cases}$$

General idea to construct a locally implicit method

We consider

$$\frac{dy(t)}{dt} = Ay(t) + F(t), \quad (1)$$

After discretization we compute $y(t_n + \xi\Delta t)$ as follows

$$\begin{aligned} y(t_n + \xi\Delta t) = & y(t_n) + \underbrace{\int_{t_n}^{t_n + \xi\Delta t} A(I - P)y(t)dt}_{\text{Coarse part}} + \underbrace{\int_{t_n}^{t_n + \xi\Delta t} (I - P)F(t)dt}_{\text{source term}} \\ & + \underbrace{\int_{t_n}^{t_n + \xi\Delta t} APy(t)dt}_{\text{Fine part}} + \underbrace{\int_{t_n}^{t_n + \xi\Delta t} PF(t)dt}_{\text{source term}} \end{aligned} \quad (2)$$

Treatment of the coarse region

For degrees of freedom (dofs) in the coarse region far from the fine region, we obtain the following expression:

$$y_{n+1} = y_n + \Delta t A(I - P) \sum_{j=0}^m \alpha_{j+1} \Delta t^j \tilde{w}_j + \Delta t(I - P) \sum_{i=1}^s b_i F_i \quad (3)$$

where α_j are the coefficients of the Optimized CFL number explicit schemes (see the thesis [N'diaye, 2017]), b_i are the weights of a quadrature rule and

$$\tilde{w}_j = A^j y(t_n) + \sum_{\ell=1}^j A^{j-\ell} Q^{(\ell-1)}(t_n).$$

Q is the polynomial that interpolates F .

Treatment of the fine region

We denote by \hat{Q} the anti-derivative of Q and we approximate the contribution for dofs in the coarse region close to the fine region to obtain:

$$y(t_n + \xi \Delta t) \approx y_n + A(I - P) \sum_{j=0}^m \alpha_{j+1} (\xi \Delta t)^{j+1} \tilde{w}_j + (I - P) \left(\hat{Q}(t_n + \xi \Delta t) - \hat{Q}(t_n) \right) + \int_{t_n}^{t_n + \xi \Delta t} APy(t) + PF(t) dt \quad (4)$$

We introduce $\tau = \xi \Delta$, $\tilde{y}(\tau) = y(t_n + \tau)$ and differentiate (4), like in [Mehlin et al., 2015], to get:

$$\frac{d\tilde{y}(\tau)}{d\tau} = \overbrace{A(I - P) \sum_{j=0}^m (j+1) \alpha_{j+1} \tau^j \tilde{w}_j}^{\text{updated source term}} + (I - P)Q(t_n + \tau) + PF(t_n + \tau) + AP\tilde{y}(\tau) \quad (5)$$

We use unconditionally stable implicit method developed in [Barucq et al., 2017] to solve the ODE (5).

Splitting of the Mesh into fine and coarse region

We assume that the domain Ω is meshed with elements K_i such that

$$\Omega = \bigcup K_i.$$

- We define Ω_i containing K_i and adjacent elements,
- then we define the size of K_i by:

$$h_i = \min_{\mathbf{e} \text{ edge of } \Omega_i} \text{length}(\mathbf{e}).$$

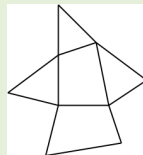


Figure: Example of 2D small meshes Ω_i .

Given a reference size h_{ref} , we split the domain using the following rule:

$$\begin{cases} \text{if } h_i \leq h_{ref}, K_i \in \Omega^{fine} = \text{fine region} \\ \text{if } h_i > h_{ref}, K_i \in \Omega^{coarse} = \text{coarse region} \end{cases}$$

2 Numerical convergence

Acoustic wave equation

We consider the first order formulation of the acoustic wave equation

$$\left\{ \begin{array}{l} \rho \partial_t u - \operatorname{div} \mathbf{v} = f, \quad \forall (x, t) \in \Omega \times I \\ \mu^{-1} \partial_t \mathbf{v} - \nabla u = 0, \quad \forall (x, t) \in \Omega \times I \\ u(x, 0) = \partial_t u(x, 0) = 0, \quad \forall x \in \Omega \quad (\text{null initial conditions}) \\ \mu \partial_n u = 0, \quad x \in \Gamma_N \quad (\text{Neumann condition}) \end{array} \right. \quad (6)$$

- Ω is the computational domain
- I is the time interval
- u is the pressure field
- \mathbf{v} is the displacement wave field
- $\rho = \frac{1}{\rho_f c^2}$ and $\mu = \frac{1}{\rho_f}$
- ρ_f is the fluid density
- c is the wave speed

Convergence curves

- ✓ 8th order HDG is used on a regular mesh covering $[-5, 5]^2$, and $\rho = \mu = 1$.
- ✓ The source term in space is $f(x, y) = \exp(-\alpha_0(x^2 + y^2))$, $\alpha_0 \approx -\frac{\log(10^{-6})}{4}$.
- ✓ $I = [0, 200]$, the temporal source is a Ricker, with frequency $f_0 = 0.48$.

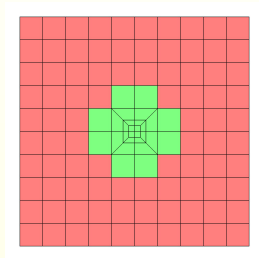
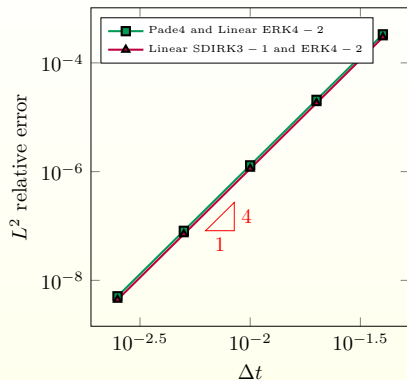


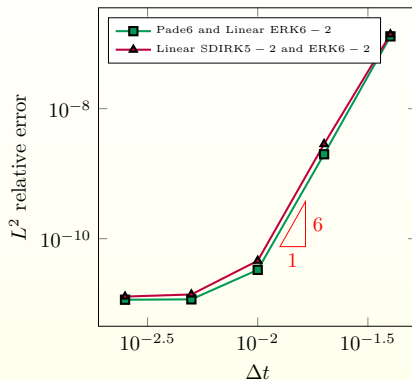
Figure: Mesh used for the convergence curves of the locally implicit method. Fine region in green.

- 116 elements
- 2 268 degrees of freedom
- $\Delta t_{max} \approx 0.005$ for classical ERK4
- $\Delta t_{max} \approx 0.0133$ for optimized ERK4 with 2 additional stages.
- $\Delta t_{max} \approx 0.04$ for the locally implicit method of order 4.

Convergence curves



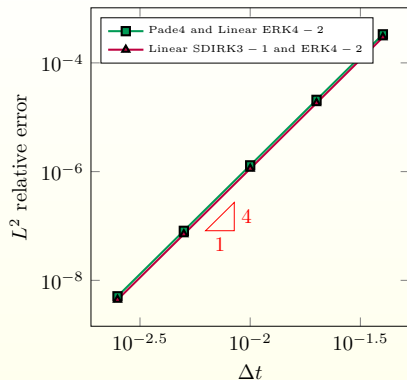
(a) Order 4



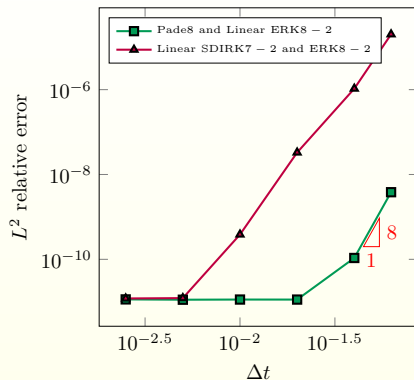
(b) order 6

Figure: Relative L^2 error between numerical solution and the reference solution for $t = 200$ with respect to the time step. Comparison of locally implicit methods of order 4 and 6 (Padé and Linear-SDIRK schemes combined with Linear-ERK schemes). The space discretization error is about 10^{-11} .

Convergence curves



(a) Order 4



(b) Order 8

Figure: Relative L^2 error between numerical solution and the reference solution for $t = 200$ with respect to the time step. Comparison of locally implicit methods of order 4 and 8 (Padé and Linear-SDIRK schemes combined with Linear-ERK schemes). The space discretization error is about 10^{-11} .

On going works and perspectives

On going works

- Parallelization of the locally implicit method.
- Comparison of explicit, implicit and locally implicit methods for 3D problems.

Perspectives

- Comparison of locally implicit and the local time stepping technique.
- Combine locally implicit methods with the local time stepping technique.

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Thank you for your attention.

Questions?

3 References

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