Linearly Stabilized Schemes for the Time Integration of Stiff Nonlinear PDEs

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Introduction

1. Focus on time stepping for stiff nonlinear PDEs.
   - Stability
   - Accuracy
   - Efficiency
   - Simplicity

Example

Consider the heat equation,

$$u_t = u_{xx}, \quad x \in \Omega, t > 0.$$

Discretize in space:

$$U' = LU, \quad U \in \mathbb{R}^N, t > 0.$$

Explicit: $U^{n+1} = G(U^n, U^{n-1}, \ldots, LU^n, LU^{n-1}, \ldots)$, but $\Delta t \leq Ch^2$.
Implicit: $AU^{n+1} = b$; unconditionally stable, but must solve a linear system.

Example

Now compare with

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{1}{u}, \quad x \in \Omega, t > 0.$$

and

$$U' = F(U), \quad U \in \mathbb{R}^N, t > 0.$$

Explicit: $U^{n+1} = G(U^n, U^{n-1}, \ldots, F(U^n), F(U^{n-1}), \ldots)$, but $\Delta t \leq Ch^2$.
Implicit: $AU^{n+1} = b(U^{n+1})$; unconditionally stable, but must solve a
nonlinear system because nonlinearity is in the stiff term.

Example

Comparing side-by-side:

$$u_t = u_{xx}, \quad x \in \Omega, t > 0,$$

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{1}{u}, \quad x \in \Omega, t > 0,$$

Explicit: $\Delta t \leq Ch^2$
Implicit: unconditionally stable;
solution to linear system

Explicit: $\Delta t \leq Ch^2$
Implicit: unconditionally stable;
solution to nonlinear system

Summary: What We Like

Explicit: simple; handles nonlinear terms with no added difficulty.
Implicit: large time steps

Example

Modify the equation,

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{1}{u} - u_{xx} + u_{xx}, \quad x \in \Omega, t > 0,$$

$$\downarrow$$

$$U' = F(U) - LU + LU, \quad U \in \mathbb{R}^N, t > 0,$$

and use implicit-explicit time stepping, e.g.

$$\frac{U^{n+1} - U^n}{\Delta t} = F(U^n) - LU^n + LU^{n+1}.$$

Linear Stability

More generally, from $U' = F(U)$, we can modify as

$$U' = \underbrace{F(U) - pLU}_{(\star)} + pLU, \quad p > 0,$$

and apply a time stepping scheme that treats $(\star)$ explicitly.
Key question: Is this unconditionally stable?

Scalar test equation

Standard case:

$$U' = F(U)$$

Linearize $\rightarrow$ Diagonalize $\rightarrow$ Test equation:

$$u' = \lambda u$$

Apply time stepping method:

With linear modification:

$$U' = F(U) - pLU + pLU$$

Linearize $\rightarrow$ Diagonalize $\rightarrow$ Test equation:

$$u' = \lambda u - p\lambda u + p\lambda u$$
$$= (1 - p)\lambda u + p\lambda u$$

$$u^{n+1} = \xi(\lambda \Delta t)u^n$$

Stability constraint:

$$|\xi(\lambda \Delta t)| \leq 1$$

Implicit-explicit Euler

Applied to the test equation $u' = (1 - p)\lambda u + p\lambda u$, yields

$$\frac{u^{n+1} - u^n}{\Delta t} = (1 - p)\lambda u^n + p\lambda u^{n+1}.$$

The amplification factor is

$$\xi_1(\lambda\Delta t) = \frac{1 + (1 - p)\lambda\Delta t}{1 - p\lambda\Delta t}.$$

Impose unconditional stability:

$$|\xi_1(\lambda\Delta t)| \leq 1 \text{ for all } \lambda\Delta t < 0 \implies p \geq 1/2.$$

Explicit-implicit-null (EIN)

Use Richardson extrapolation to get second order. The amplification factor is

$$\xi_{EIN}(\lambda\Delta t) = 2\xi_1^2(\lambda\Delta t/2) - \xi_1(\lambda\Delta t).$$

and

$$|\xi_{EIN}(\lambda\Delta t)| \leq 1 \text{ for all } \lambda\Delta t < 0 \implies p \geq 2/3.$$

Implicit-explicit multistep methods

An alternative for second and higher order methods: IMEX multistep methods.

Order	Method	$p \in$
2	SBDF2	$[3/4, \infty)$
	CNAB	$[1, \infty)$
	mCNAB	$[8/9, \infty)$
	CNLF	$[1/2, \infty)$
3	SBDF3	$[7/8, 2]$
4	SBDF4	$[11/12, 5/4]$

Comparing the methods

Do the methods work as advertised?
Examine this with two test problems,

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{1}{u},$$

and

$$u_t = \Delta(u^5).$$

Test Problem 1

First test problem:

$$u_t = \frac{u_{xx}}{1 + u_x^2} - \frac{1}{u}, \quad 0 < x < 10, \quad t > 0,$$

with initial condition

$$u(x, 0) = 1 + 0.10 \sin\left(\frac{\pi}{5} x\right),$$

and boundary conditions $u(0, t) = 1 = u(10, t)$.

Numerical convergence test

Figure: Numerical convergence of linearly stabilized schemes.

Spatial discretization: Uniform grid, centred differences, N=2048.
Reference solution: Explicit third order Runge-Kutta, $\Delta t = 1.46 \times 10^{-5}$.

Failure of SBDF3 and SBDF4

Test Problem 2

Second test problem:

$$u_t = \Delta(u^5), \quad (x, y) \in [0, 1]^2, \quad t > 0,$$

with initial and boundary conditions set such that the exact solution is

$$u(x, y, t) = \left(\frac{4}{5}(2t + x + y)\right)^{1/4}.$$

Numerical convergence test

Figure: Numerical convergence of linearly stabilized schemes.

Spatial discretization: second order centred differences; N=2048.
Reference solution: explicit third order Runge-Kutta, $\Delta t = 1.46 \times 10^{-5}$.

Error constant

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