



Math 673

Multigrid Methods: A Mostly Matrix-Based Approach

Chapter 04: A Modern Energy-Norm Analysis of the Two-Grid Method

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Chapter 04

A Modern Energy-Norm Analysis of the Two-Grid Method

Introduction



Like in the last chapter, we will consider the finite element approximation of the model problem in 1D:

$$\begin{cases} -u'' &= f, & \text{in } \Omega = (0, 1), \\ u &= 0, & \text{on } \partial\Omega = \{0, 1\}. \end{cases} \quad (1)$$

We will again use a uniform mesh and prove that the two-grid algorithm converges, borrowing many of the results from the previous chapter. But, the analysis style in this chapter will foreshadow the more general, and more modern, style used in the later chapters. In particular, the convergence theory will depend upon two properties, an *approximation property* and a *smoothing property*.

The reader will quickly realize how much simpler and more powerful is this modern energy approach to convergence. It is nothing short of remarkable.



The Approximation Property

Preliminaries



Recall we have defined the level-1 stiffness matrix, $A_1 = [a_{1,i,j}] \in \mathbb{R}^{n_1 \times n_1}$, by the following equations:

$$a_{1,i,j} = (\psi'_{1,j}, \psi'_{1,i})_{L^2(0,1)} = (\psi'_{1,i}, \psi'_{1,j})_{L^2(0,1)}, \quad 1 \leq i, j \leq n_1.$$

This matrix is, recall, SPD, and is therefore orthogonally diagonalizable

$$A_1 = V_1 D_1 V_1^\top,$$

where V_1 is the orthogonal matrix containing the normalized eigenvectors of A_1 ,

$$V_1 = \begin{bmatrix} \left| \begin{array}{c} \tilde{\mathbf{v}}_1^{(1)} \end{array} \right| & \left| \begin{array}{c} \tilde{\mathbf{v}}_1^{(2)} \end{array} \right| & \cdots & \left| \begin{array}{c} \tilde{\mathbf{v}}_1^{(n_1)} \end{array} \right| \end{bmatrix} \in \mathbb{R}^{n_1 \times n_1}, \quad \tilde{\mathbf{v}}_1^{(k)} = \frac{\mathbf{v}_1^{(k)}}{\|\mathbf{v}_1^{(k)}\|_1}, \quad 1 \leq k \leq n_1,$$

and D_1 is the diagonal matrix containing the eigenvalues of A_1 ,

$$D_1 = \text{diag} \left(\lambda_1^{(1)}, \lambda_1^{(2)}, \dots, \lambda_1^{(n_1)} \right) \in \mathbb{R}^{n_1 \times n_1}.$$



Preliminaries

Recall the eigenvalues, $\lambda_1^{(k)}$, and eigenvectors, $\mathbf{v}_1^{(k)}$ of A_1 are defined by

$$\lambda_1^{(k)} = \frac{4}{h_1} \sin^2 \left(\frac{k\pi h_1}{2} \right) = \frac{2}{h_1} (1 - \cos(k\pi h_1)). \quad (2)$$

and

$$\left[\mathbf{v}_1^{(k)} \right]_i = v_{1,i}^{(k)} = \sin(k\pi x_{1,i}), \quad 1 \leq i \leq n_1, \quad (3)$$

respectively. Since A_1 is SPD, we can define its square root as

$$A_1^{1/2} = V_1 D_1^{1/2} V_1^\top,$$

where

$$D_1^{1/2} = \text{diag} \left(\sqrt{\lambda_1^{(1)}}, \sqrt{\lambda_1^{(2)}}, \dots, \sqrt{\lambda_1^{(n_1)}} \right) \in \mathbb{R}^{n_1 \times n_1}.$$

Of course, $A_1^{1/2}$ is SPD, and $A_1^{1/2} A_1^{1/2} = A_1$.

Preliminaries



Now, recall, for any $\mathbf{v}_1 \in \mathbb{R}^{n_1}$,

$$\begin{aligned}\|\mathbf{v}_1\|_{A_1} &:= \sqrt{(\mathbf{v}_1, \mathbf{v}_1)_{A_1}} \\ &= \sqrt{(A_1 \mathbf{v}_1, \mathbf{v}_1)_1} \\ &= \sqrt{(A_1^{1/2} \mathbf{v}_1, A_1^{1/2} \mathbf{v}_1)_1} \\ &= \|A_1^{1/2} \mathbf{v}_1\|_1.\end{aligned}$$

In a similar way, we can define

$$\begin{aligned}\|\mathbf{v}_1\|_{A_1^2} &:= \sqrt{(A_1^2 \mathbf{v}_1, \mathbf{v}_1)_1} \\ &= \sqrt{(A_1 \mathbf{v}_1, A_1 \mathbf{v}_1)_1} \\ &= \|A_1 \mathbf{v}_1\|_1.\end{aligned}$$



Lemma

Suppose that the two-level grid is uniform and nested and A_0 satisfies the Galerkin condition. Then,

$$\left\| (I_1 - \tilde{P}_1) \mathbf{v}_1 \right\|_1 = \sqrt{2\Lambda_1^{-1}} \left\| (I_1 - \tilde{P}_1) \mathbf{v}_1 \right\|_{A_1}, \quad (4)$$

for all $\mathbf{v}_1 \in \mathbb{R}^{n_1}$, where

$$\Lambda_1 := \frac{4}{h_1}.$$



Proof.

Expand \mathbf{v}_1 in the basis of eigenvectors of A_1 :

$$\mathbf{v}_1 = \sum_{k=1}^{n_1} v_{1,k} \mathbf{v}_1^{(k)}.$$

Recall that

$$(\mathbf{I}_1 - \tilde{\Pi}_1) \mathbf{v}_1^{(k)} = \mathbf{S}_k \mathbf{v}_1^{(k)} + \mathbf{S}_k \mathbf{v}_1^{(k')}, \quad (\text{low frequency})$$

for $1 \leq k \leq n_0 + 1$, and

$$(\mathbf{I}_1 - \tilde{\Pi}_1) \mathbf{v}_1^{(k')} = \mathbf{C}_k \mathbf{v}_1^{(k)} + \mathbf{C}_k \mathbf{v}_1^{(k')}, \quad (\text{high frequency})$$

for $1 \leq k \leq n_0 + 1$.



Proof (Cont.)

Then

$$\begin{aligned}\|(I_1 - \tilde{N}_1)\mathbf{v}_1\|_1^2 &= \left((I_1 - \tilde{N}_1)\mathbf{v}_1, (I_1 - \tilde{N}_1)\mathbf{v}_1 \right)_1 \\ &= (n_1 + 1) \sum_{k=1}^{n_0+1} \delta_k \gamma_k^2,\end{aligned}$$

where

$$\delta_k = \begin{cases} \frac{1}{2}, & k = n_0 + 1, \\ 1, & \text{otherwise,} \end{cases}$$

and

$$\gamma_k := \mathbf{v}_{1,k} \mathbf{S}_k + \mathbf{v}_{1,k'} \mathbf{C}_k.$$



Proof (Cont.)

Similarly,

$$\begin{aligned}
 \left\| (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right\|_{A_1}^2 &= \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right)_{A_1} \\
 &= \left(A_1^{1/2} (I_1 - \tilde{\Pi}_1) \mathbf{v}_1, A_1^{1/2} (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right)_1 \\
 &= (n_1 + 1) \sum_{k=1}^{n_0+1} \delta_k \gamma_k^2 \left(\frac{\lambda_1^{(k)} + \lambda_1^{(k')}}{2} \right) \\
 &= \frac{2}{h_1} (n_1 + 1) \sum_{k=1}^{n_0+1} \delta_k \gamma_k^2 \\
 &= \frac{1}{2} \Lambda_1 \left\| (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right\|_1^2.
 \end{aligned}$$





Remark

We will prove a similar result later in the general FEM framework, where, in particular, the meshes need not be uniform. In that setting, we will seek to prove that there is a constant $C_{A0} > 0$ such that

$$\left\| (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right\|_1 \leq C_{A0} \sqrt{\Lambda_1^{-1}} \left\| (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right\|_{A_1}, \quad (5)$$

for all $\mathbf{v}_1 \in \mathbb{R}^{n_1}$.



Theorem (The Approximation Property)

Suppose that the two-level grid is uniform and nested and A_0 satisfies the Galerkin condition. For any $\mathbf{v}_1 \in \mathbb{R}^{n_1}$,

$$\left\| (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right\|_{A_1} \leq C_{A0} \sqrt{\Lambda_1^{-1}} \|\mathbf{v}_1\|_{A_1^2}, \quad (6)$$

where

$$\Lambda_1 := \frac{4}{h_1} \quad \text{and} \quad C_{A0} = \sqrt{2}.$$



Proof.

Let $\mathbf{v}_1 \in \mathbb{R}^{n_1}$ be arbitrary. Then

$$\begin{aligned}\|(I_1 - \tilde{P}_1)\mathbf{v}_1\|_{A_1}^2 &= \left(A_1(I_1 - \tilde{P}_1)\mathbf{v}_1, (I_1 - \tilde{P}_1)\mathbf{v}_1 \right)_1 \\ &= \left((I_1 - \tilde{P}_1)\mathbf{v}_1, A_1(I_1 - \tilde{P}_1)\mathbf{v}_1 \right)_1 \\ &= \left((I_1 - \tilde{P}_1)\mathbf{v}_1, A_1\mathbf{v}_1 \right)_1 - \left((I_1 - \tilde{P}_1)\mathbf{v}_1, A_1\tilde{P}_1\mathbf{v}_1 \right)_1.\end{aligned}$$



Proof (Cont.)

The second term on the RHS is zero, as we now show:

$$\begin{aligned}
 \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, \tilde{\Pi}_1 \mathbf{v}_1 \right)_{A_1} &= \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, A_1 \tilde{\Pi}_1 \mathbf{v}_1 \right)_1 \\
 &= \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, A_1 (P_0 A_0^{-1} R_0 A_1) \mathbf{v}_1 \right)_1 \\
 &= \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, (A_1 P_0 A_0^{-1} R_0) A_1 \mathbf{v}_1 \right)_1 \\
 &= \left((A_1 P_0 A_0^{-1} R_0)^\top (I_1 - \tilde{\Pi}_1) \mathbf{v}_1, A_1 \mathbf{v}_1 \right)_1 \\
 &= \left(\tilde{\Pi}_1 (I_1 - \tilde{\Pi}_1) \mathbf{v}_1, \mathbf{v}_1 \right)_{A_1} \\
 &= 0,
 \end{aligned}$$

since

$$\tilde{\Pi}_1 (I_1 - \tilde{\Pi}_1) = \tilde{\Pi}_1 - \tilde{\Pi}_1^2 = \tilde{\Pi}_1 - \tilde{\Pi}_1 = O_1.$$



Proof (Cont.)

Therefore,

$$\begin{aligned} \left\| (I_1 - \tilde{N}_1) \mathbf{v}_1 \right\|_{A_1}^2 &= \left((I_1 - \tilde{N}_1) \mathbf{v}_1, A_1 \mathbf{v}_1 \right)_1 \\ &\stackrel{\text{C.S.}}{\leq} \left\| (I_1 - \tilde{N}_1) \mathbf{v}_1 \right\|_1 \|A_1 \mathbf{v}_1\|_1 \\ &= \left\| (I_1 - \tilde{N}_1) \mathbf{v}_1 \right\|_1 \|\mathbf{v}_1\|_{A_1^2} \\ &\stackrel{(4)}{=} \sqrt{2\Lambda_1^{-1}} \left\| (I_1 - \tilde{N}_1) \mathbf{v}_1 \right\|_{A_1} \|\mathbf{v}_1\|_{A_1^2}. \end{aligned}$$

The result follows. □



Corollary

Suppose that the two-level grid is uniform and nested and A_0 satisfies the Galerkin condition. Then

$$\left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, (I_1 - \tilde{\Pi}_1) \mathbf{v}_1 \right)_{A_1} = \left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, \mathbf{v}_1 \right)_{A_1},$$

or, equivalently,

$$\left((I_1 - \tilde{\Pi}_1) \mathbf{v}_1, \tilde{\Pi}_1 \mathbf{v}_1 \right)_{A_1} = 0.$$



Remark

*Estimate (6) is called an **approximation property** with constant $C_{A0} > 0$.*



Richardson's Smoother



Richardson's Smoother

In this section, we want to change our smoothing algorithm from damped Jacobi to Richardson's method. It turns out that this change is mostly cosmetic, as the underlying structure for the smoother will be essentially the same. Specifically, our Richardson smoother will have the following error transfer matrix:

$$K_1 = I_1 - \frac{1}{\Lambda_1} A_1, \quad \Lambda_1 = \frac{4}{h_1}.$$

Recall

$$\lambda_1^{(k)} = \frac{2}{h_1} (1 - \cos(k\pi h_1)).$$

So,

$$0 < \lambda_1^{(1)} < \lambda_1^{(2)} < \dots < \lambda_1^{(n_1)} = \rho(A_1) < \frac{4}{h_1} = \Lambda_1.$$

Λ_1 is almost the spectral radius of A_1 ; the last estimate is asymptotically sharp.

Relation to Damped Jacobi



For damped Jacobi, recall that

$$\begin{aligned} K_1 = K_1(\omega) &= I_1 - \omega D^{-1} A_1 \\ &= I_1 - \omega \frac{h_1}{2} A_1. \end{aligned}$$

If we take $\omega = \frac{1}{2}$ in damped Jacobi, we get our new Richardson smoother.



Richardson's Smoother

The error transfer matrix, which, for Richardson's method is

$$K_1 = I_1 - \Lambda_1^{-1} A_1 = I_1 - \frac{h_1}{4} A_1,$$

has the following eigenvalues:

$$\begin{aligned}\mu_1^{(k)}\left(\frac{1}{2}\right) &= \frac{1}{2} \cos(k\pi h_1) + 1 - \frac{1}{2} \\ &= 1 - \frac{\lambda_1^{(k)}}{\Lambda_1}.\end{aligned}$$

Consulting the figure on the next page, it follows easily that

$$\left| \mu_1^{(k)}\left(\frac{1}{2}\right) \right| = \mu_1^{(k)}\left(\frac{1}{2}\right) \leq \mu_1^{(n_0+1)}\left(\frac{1}{2}\right) = \frac{1}{2}, \quad n_0 + 1 \leq k \leq n_1.$$

In other words the smoother reduces all high frequency modes of the error by at least half.



Richardson's Smoother

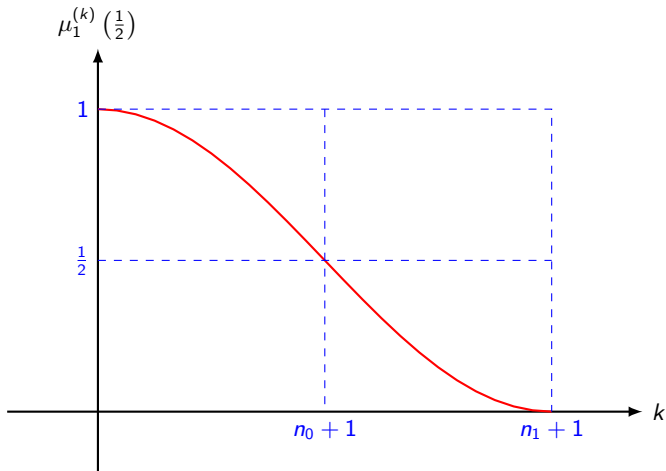


Figure: Eigenvalues of the error transfer matrix for the Richardson smoother.



The Smoothing Property



Before we establish the so-called *smoothing property*, we need a technical lemma.

Lemma

For any $m \in \mathbb{N}$,

$$\max_{0 \leq x \leq 1} x(1-x)^{2m} \leq \frac{1}{2m}. \quad (7)$$



Proof.

Define, for any $m \in \mathbb{N}$,

$$f(x) = x(1-x)^{2m}, \quad x \in [0, 1].$$

Observe that

$$f(0) = f(1) = 0,$$

and, otherwise

$$f(x) > 0, \quad \forall x \in (0, 1).$$

The derivative of f is

$$f'(x) = (x-1)^{2m} + x(2m)(x-1)^{2m-1},$$

and there is a single zero for $f'(x)$ in $(0, 1)$, which we label x_0 . It is easy to show that

$$x_0 = \frac{1}{2m+1}.$$



Proof (Cont.)

We leave it as an exercise for the reader to show that f achieves its maximum value at x_0 on the interval $[0, 1]$. Evaluating at x_0 and estimating, we find

$$f(x_0) = \frac{1}{2m+1} \left(\frac{2m}{2m+1} \right)^{2m} \leq \frac{1}{2m+1} \leq \frac{1}{2m}.$$

The result follows. □



Theorem (The Smoothing Property)

Suppose that the two-level grid is uniform. Assume that smoothing is carried out by Richardson's method, or, equivalently, the damped Jacobi method with $\omega = \frac{1}{2}$. There is some constant $C_{S1} > 0$, such that

$$\|K_1^{m_1} \mathbf{v}_1\|_{A_1^2} \leq C_{S1} \sqrt{\frac{\Lambda_1}{m_1}} \|\mathbf{v}_1\|_{A_1}, \quad (8)$$

for all $\mathbf{v}_1 \in \mathbb{R}^{n_1}$, for any $m_1 \in \mathbb{N}$. In particular, we can take

$$C_{S1} = \sqrt{\frac{1}{2}}.$$



Proof.

First, observe that

$$\begin{aligned}\|K_1^{m_1} \mathbf{v}_1\|_{A_1^2}^2 &= \|A_1 K_1^{m_1} \mathbf{v}_1\|_1^2 \\ &= (A_1 K_1^{m_1} \mathbf{v}_1, A_1 K_1^{m_1} \mathbf{v}_1)_1.\end{aligned}$$

Using the eigenvector basis for A_1 , let us write

$$\mathbf{v}_1 = \sum_{k=1}^{n_1} v_{1,k} \mathbf{v}_1^{(k)}.$$



Proof (Cont.)

Then

$$\begin{aligned}\|K_1^{m_1} \mathbf{v}_1\|_{A_1^2}^2 &= \frac{n_1 + 1}{2} \sum_{k=1}^{n_1} \left(\lambda_1^{(k)} v_{1,k} \right)^2 \left(\mu_1^{(k)} \left(\frac{1}{2} \right) \right)^{2m_1} \\ &= \Lambda_1 \left(\frac{n_1 + 1}{2} \right) \sum_{k=1}^{n_1} \left(\frac{\lambda_1^{(k)}}{\Lambda_1} \right) \left(1 - \frac{\lambda_1^{(k)}}{\Lambda_1} \right)^{2m_1} \lambda_1^{(k)} v_{1,k}^2 \\ &\leq \Lambda_1 G(m_1) \left(\frac{n_1 + 1}{2} \right) \sum_{k=1}^{n_1} \lambda_1^{(k)} v_{1,k}^2 \\ &= \Lambda_1 G(m_1) \|\mathbf{v}_1\|_{A_1}^2,\end{aligned}$$

where

$$G(m) := \max_{1 \leq k \leq n_1} \left(\frac{\lambda_1^{(k)}}{\Lambda_1} \right) \left(1 - \frac{\lambda_1^{(k)}}{\Lambda_1} \right)^{2m}.$$



Proof (Cont.)

Upon rescaling and using the lemma we just proved, we have

$$\begin{aligned} G(m) &\leq \max_{0 \leq x \leq 1} x(1-x)^{2m} \\ &\stackrel{(7)}{\leq} \frac{1}{2m}. \end{aligned}$$

Therefore

$$\|K_1^{m_1} \mathbf{v}_1\|_{A_1^2} \leq \sqrt{\frac{1}{2}} \sqrt{\frac{\Lambda_1}{m_1}} \|\mathbf{v}_1\|_{A_1}, \quad (9)$$

and the result follows with $C_{S1} = \sqrt{\frac{1}{2}}$. □



Remark

*Estimate (8) is called a **smoothing property** with constant $C_{S1} > 0$.*



Convergence in the Energy Norm



Now that we have the powerful smoothing and approximation properties, the energy-norm convergence of the two-grid method is simple matter.

Theorem (Convergence of the One-Sided Two-Grid Method)

Suppose that the two-level grid is uniform and nested and A_0 satisfies the Galerkin condition. Suppose that smoothing is done by the Damped Jacobi method, using $\omega = \frac{1}{2}$ (Richardson), with $m_1 > 0$ and $m_2 = 0$. Then the (one-sided) two-grid method converges, provided m_1 is sufficiently large. Moreover, we have the error estimate

$$\left\| \mathbf{e}_1^{\ell+1} \right\|_{A_1} \leq C_{A0} C_{S1} m_1^{-1/2} \left\| \mathbf{e}_1^{\ell} \right\|_{A_1},$$

where $C_{A0}, C_{S1} > 0$ are as given in the previous results. Since we can assume $C_{A0} C_{S1} = 1$, it follows that the method converges if $m_1 \geq 2$.



Proof.

Recall, the error transfer matrix in this case is

$$E_1 = (I_1 - \tilde{\Pi}_1)K_1^{m_1}.$$

So

$$\begin{aligned}\|e_1^{\ell+1}\|_{A_1} &= \|(I_1 - \tilde{\Pi}_1)K_1^{m_1}e_1^\ell\|_{A_1} \\ &\stackrel{(6)}{\leq} C_{A0}\sqrt{\Lambda_1^{-1}}\|K_1^{m_1}e_1^\ell\|_{A_1^2} \\ &\stackrel{(8)}{\leq} C_{A0}\sqrt{\Lambda_1^{-1}}C_{S1}\sqrt{\Lambda_1}m_1^{-\frac{1}{2}}\|e_1^\ell\|_{A_1} \\ &= C_{A0}C_{S1}m_1^{-\frac{1}{2}}\|e_1^\ell\|_{A_1}.\end{aligned}$$





Remark

In this simplified setting, we know that $C_{A0}C_{S1} = 1$. For the more general FEM case that we will explore in the future – for which the h_1 -independent constants $C_{A0} > 0$ and $C_{S1} > 0$, may not be known explicitly – we will still be guaranteed that the method converges at a uniform, h_1 -independent rate provide $m_1 \geq 1$ is large enough so that

$$0 < C_{A0}C_{S1}m_1^{-\frac{1}{2}} < 1.$$